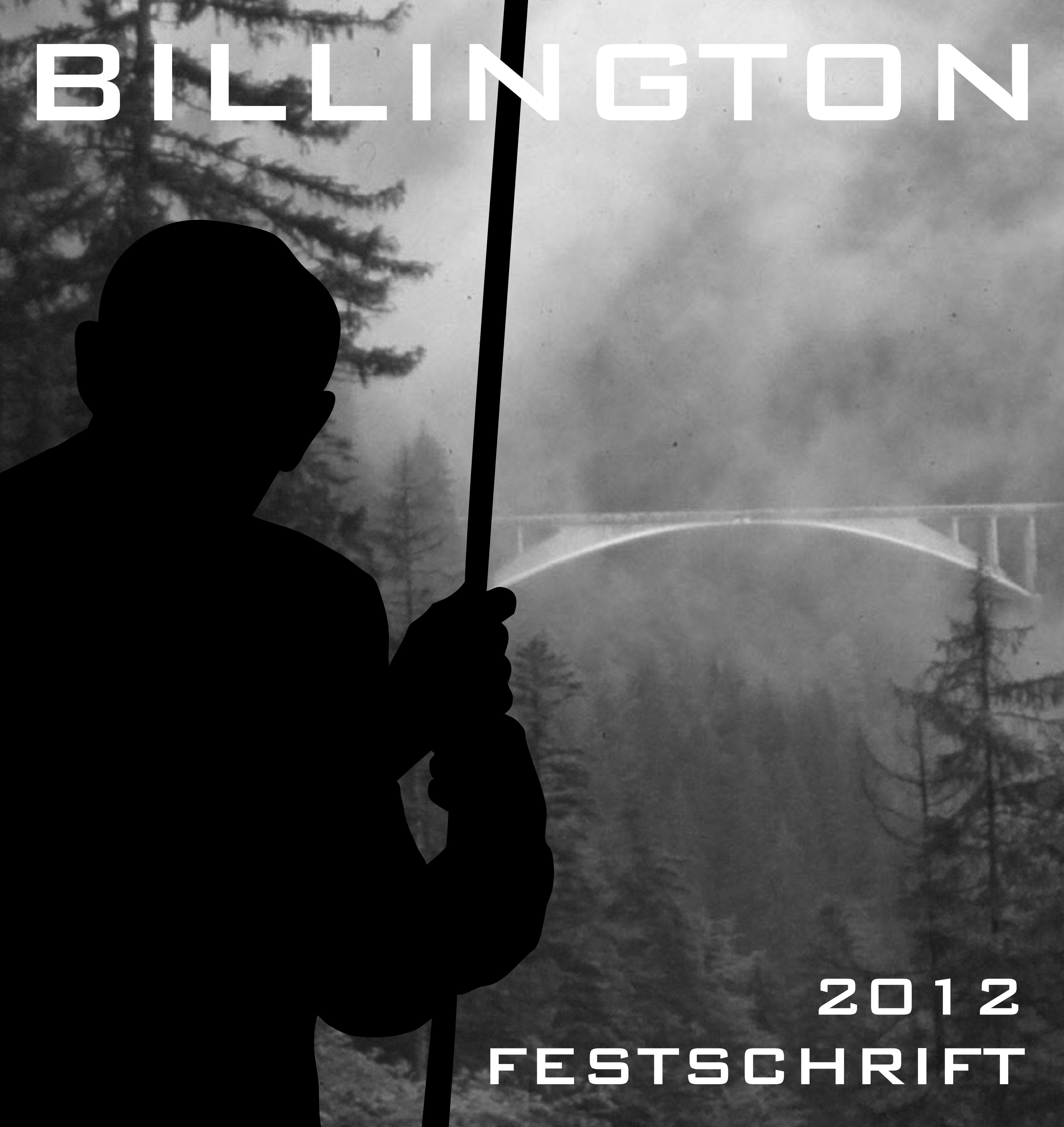
BILLINGTON



2012 FESTSCHRIFT

FESTSCHRIFT BILLINGTON

2012

overleaf

The Salginatobel bridge, designed by Robert Maillart in 1928 and completed in 1930, was selected for this crossing as the low bid among seven proposals in steel and twelve proposals in concrete. The art world discovered this bridge in the 1940s through the work of Sigfried Giedion and Max Bill. Only later did the bridge and its designer achieve prominence in the engineering world, largely through the scholarship of Professor David P. Billington. Now a work of international significance, the Salgina crossing has come to symbolize the epitome of structural design as an art form in its own right. [photo: Paul Gauvreau]

cover design by Eric M. Hines
cover photo by Annette Bögle

FESTSCHRIFT BILLINGTON

2012

Essays in Honor of David P. Billington

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International Network for Structural Art

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PREFACE

Professor David P. Billington of Princeton University has inspired generations of students to understand engineering, art, science and society as a unity, through the examples of great individuals and their work. Billington has characterized Structural Art as a movement awaiting a vocabulary,[1] and his scholarship has given enduring form to this vocabulary. The questions raised by his scholarship are eternal—what are the relationships between engineering and science, engineering and architecture, and structures and machines?

The importance of this discussion extends beyond the design of beautiful structures. In its engagement of the scientific, social and symbolic characteristics of constructed engineering work, structural art addresses fundamental questions regarding the relationships between civilization's most ancient ideals: truth, goodness and beauty. Billington's scholarship implies that in order to understand these eternal values in our modern world, it is necessary to recognize the new realities wrought by engineers since the industrial revolution. Structural art is important to culture in general because it symbolizes the potential for harmonious relationships between engineering, science, art and society. It is accessible to everyone because it can be seen and touched. Its scale provides a visceral experience of the power engaged by engineers in creating the modern world.

The contributors have assembled this *Festschrift* in order to honor Professor Billington's long and illustrious career. His voice has influenced countless members of our profession, encouraging us to seek the human stories behind the great works of structural engineering. It is through these stories that he has conveyed to us not only the character of the great designers themselves, but also the very ideas and contexts that have made great designs possible.

The title *Festschrift*, literally translated, means "celebration writing," and is taken from the German academic tradition of honoring a mentor through the writing and presentation of original scholarly work. We have chosen this title in recollection of more than one *Festschrift* stumbled upon while working alongside Professor Billington in his Maillart Archive at Princeton University.

We offer this collection of essays in celebration of Professor Billington's 85th birthday. The year 2012 is auspicious for more than one reason, however. It is also the 200th anniversary of structural art as originally discussed by Thomas Telford in his 1812 article "Bridge" in the *Edinburgh Encyclopedia*;[2] the 140th anniversary of the birth of Robert Maillart; and the 40th anniversary of the symposium at Princeton University "Civil Engineering: History, Heritage and the Humanities," whose participants included Max Bill, Marie-Claire Blumer-Maillart, Christian Menn, Felix Candela and Fazlur Khan among others. In fact, if we stretch our imaginations just a little, it is also the 10th anniversary of the community that forms the intellectual core of the *International Network for Structural Art,* as planning began in 2002 for "A Symposium in Honor of David P. Billington at Seventy-Five and Forty-Five Years of Teaching."

For the past 10 years, Professor Billington has both generously and tenaciously gathered a diverse group of colleagues in Princeton to discuss issues related to teaching university students about structural art. In the past two years, these gatherings have developed their own momentum and promise to become a mainstay in future discussions of structural engineering as an artistic discipline in its own right. We see the future of these discussions as the next chapter in a tradition of scholarship founded by Professor Billington. It is our aim to strengthen international dialogue on structural art, with the hope of continuing to fulfill the promise "that structures, the forgotten half of modern technology, provide a key to the revival of public life."[3]

More than one of us have been advised at one time or another by Professor Billington that a scholarly discipline is defined by its members publishing their work for review, critique and discussion by one another. More than one of us have also experienced the challenge of publishing serious scholarship on the human character of engineering in a culture where quality is often defined in less sophisticated terms. The publication of this *Festschrift* represents a deliberate attempt to move from a collection of individual members to a new discipline that blurs the boundaries between technical engineering research and the history of the modern world. For the inspiration and the standards of quality behind this new discipline, we have Professor Billington to thank.

In our struggle to define the future of our discipline we have assumed diverse points of view, however we seem to have converged on the importance of process. Whether the process in question is a design process, a cultural process, a political process, or an educational process, the following essays provide insight into the creation of engineered structures.

On behalf of all of the students, colleagues, family and friends that have participated in what has evolved into the *International Network for Structural Art,* we would like to thank Professor Billington and the Department of Civil and Environmental Engineering at Princeton University for hosting the meetings in recent years that have given rise to our present work. We would like to thank members of the *Network* who peer reviewed these papers. We would also like to thank David P. Billington Jr. for supplying the highlights of Professor Billington's life. Finally, we would like to thank Phyllis Billington, J. Wayman (Flash) Williams and Kathy Posnett for their consistent support and participation in these meetings.

Eric M. Hines, Stephen G. Buonopane and Maria E. M. Garlock

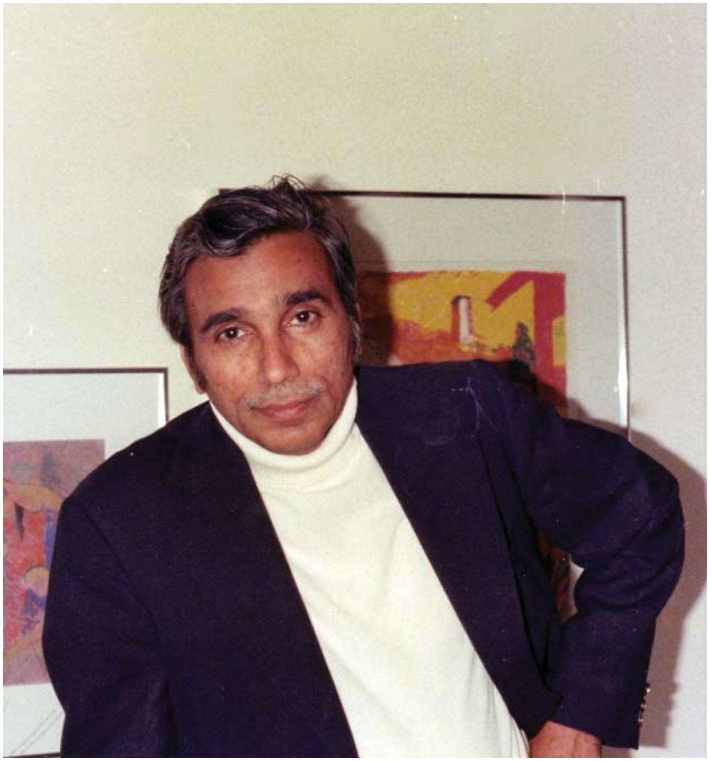
1. David P. Billington, *The Tower and the Bridge* (Princeton, New Jersey: Princeton University Press, 1983) p. 4.
2. Ibid., pp. 5, 6, 38.
3. Ibid., p. 4.

TEACHING SOCIAL AND MULTI-DIMENSIONAL ASPECTS OF STRUCTURES THROUGH FAZLUR KHAN

Sigrid M. Adriaenssens and Maria E. Moreyra Garlock

Figure 1

Fazlur Rahman Khan (1929-1982) [image courtesy Yasmin Khan].



Abstract

This paper adds to the body of knowledge that aims at imbuing undergraduate students with the ability to draw upon successful precedent engineering approaches by researching works of structural art. The paper presents a series of deficiencies in current structural engineering curricula and introduces a remedial pilot studio based research course '*CEE463: A social and multi-dimensional exploration of structures*'. This course, held at Princeton University in Fall 2010, focused on the works and major innovations of Fazlur Rahman Khan (1929-1982), structural artist of urban building forms. The paper is organized in two parts. Part One shows how Khan approached and developed engineering projects. Part Two discusses how we used Khan as a case study in our course and how we implemented his design 'toolbox' as part of the curriculum. This part also describes the pedagogical objectives; the five course components ((i) studio pedagogy, (ii) invited speakers,(iii) site visits, (iv) models and exhibition,(v) website and book); and the students' evaluations of the course. It then suggests ways of making the course transferable to other educational settings. The paper concludes how this course also teaches educators, practitioners and the general public about structural art and warmly acknowledges the inspiration for this course, the scholarship and teachings of David Billington.

Introduction

On a daily basis practicing engineers work in complex situations to which they cannot solely apply the specialized knowledge gained in academia. Structural engineering education specifically is two-dimensional, studied with analyses and sketches and, if you are lucky, with photographs of real structures (although usually the latter is not done). Structures, however, are multi-dimensional: they have three dimensions of space, plus a fourth one of time and they are developed in a specific socio-historic and political context. In such a multi-faceted framework we distinguish a number of practicing engineers as being very skillful at developing economic, efficient and elegant structures.

At the Department of Civil and Environmental Engineering (CEE) at Princeton University (PU) in Fall 2010 we taught a one semester studio course '*CEE463: A social and multi-dimensional exploration of structures*'. The course was aimed at senior students and enhanced traditional structural engineering education by addressing the described deficiencies through the following pedagogical objectives: (i) start to develop a sense for implicit knowing by studying precedents, (ii) communicate complex technical issues with peers and laymen, (iii) develop spoken, written, pictorial, analytical and numerical proficiency and (iv) reflect critically upon social, political and historic influences of past successful structural designs. These objectives serve some of the ABET accreditation requirements and serve to imbue the student with not scientific but historical knowledge by studying successful structural engineers of the past. This knowledge is needed to equip our students, once they have graduated and work in practice, with the ability to draw upon effective precedent engineering approaches. The theme of the course changes every time it is taught, and the Fall 2010 course focused on the theme of tall buildings. More specifically, we studied the works and major innovations of Fazlur Rahman Khan (1929-1982) (Fig. 1), structural designer of tall buildings that include the Sears Tower and John Hancock Center (both Chicago, IL, USA).

This class is in effect the next level of *CEE262: Structures in the Urban Environment*, which was conceived of and taught by David Billington since 1974. CEE262 centers on fourteen structural engineers with the theme of structures as a new art form arising with the Industrial Revolution and parallel to but independent of its older sister art form, architecture. Our new course, CEE463, examines the contributions of one of the engineers through a detailed examination of his seminal works. It also continues a tradition begun by David Billington at Princeton of making exhibitions of the engineer and his works. So one can say that this course was inspired by David. Further, David knew Khan personally and had collected information and photographs related to Khan from many sources, including Khan himself. This information was made available to us and was crucial for the development of our project.

This paper is divided into two parts. Part one discusses how Khan approached and developed engineering projects. To do this, we describe how Khan's teaching and research informed his designs; and also we discuss the 'tools' that Khan used to realize his projects. Part two describes in detail how using Khan as a case study, we were able to implement his design 'tools' in a course setting. For this course, we describe the pedagogical objectives, the components of the course, and finally the student's evaluation.

Part 1: Fazlur Khan and His Approach to Structural Engineering

Fazlur Khan was a structural engineer of tall buildings who worked at Skidmore Owings and Merrill (SOM) in Chicago. From 1965 to 1982, Khan significantly advanced the engineering design of urban buildings. His designs were disciplined by efficiency and economy, yet he also sought to achieve elegance. For Khan, elegance was not ornamentation, but an expression of structure, which in turns reveals the intimate relationship between forces and form. As David discussed in his Fazlur Khan lecture "Personal and Professional Reflections about a Great Engineer" at Princeton University[1], Khan worked in a three-part collaboration: (i) as a *designer* with architect Bruce Graham; (ii) as a *teacher* with architect/engineer Myron Goldsmith; and (iii) as a *scholar* with practitioner/researcher Mark Fintel. This collaborative approach to structural engineering made him unique compared to other structural artists defined by David[2]; but within the field of tall building design, it can be argued that this approach was necessary to become an innovator and structural artist of tall building forms.

This section first discusses Khan's collaborative approach to design and gives examples of how the teaching and research informed Khan's design decisions. Then we examine the 'tools' Khan used in design. In the next section we show how these 'tools' and research are implemented in the pilot course we taught.

Designer, Teacher, Scholar

At SOM, Khan worked closely with architect Bruce Graham, who was sympathetic to Khan's principle that '… *good architecture must also be good engineering and particularly good structure*.'[3] Both had mutual respect for each other and the same design ideals of efficiency, economy, and elegance, where elegance comes from an honest expression of structure. As Bruce Graham wrote of Khan: "...we worked in tandem till at the end we could think for each other. This relationship grew, not only because of sympathetic aesthetic preoccupations or the mutual respect with which we regarded each other, but also out of an indistinct vision of the city, of the city beautiful, the purpose of the cities and of the pride of human existence."[4] The designs were often constrained by space – be it the architectural program of an apartment building that would not easily permit a core, or the limit to the footprint of a major metropolis like Chicago that therefore required record breaking building heights to meet the required square-footage. These limits are what drove Khan to search for new structural solutions and new forms. He was able to innovate, with confidence, through the research he did with colleagues as a teacher and a scholar.

Khan's design ideas often came from his teaching and advising students at the Illinois Institute of Technology (IIT), which he did in collaboration with Myron Goldsmith. Goldsmith was an architect at SOM as well as a structural engineer. Probably the most famous example of how this collaboration and teaching experience resulted in a seminal structure is the example of the John Hancock Center (Fig. 2). In 1964 investor Jerry Wolman approached SOM to develop a site with residential and office use on North Michigan Avenue, Chicago. Khan and the SOM design team conceived two schemes: one that combined the two commercial and residential functions in one super tall building and one that separated them into two buildings. Khan started his engineering inquiry by devising a number of possible structural arrangements for the two building project. He discussed the advantages and costs of traditional steel versus concrete construction. The two building project seemed financially attractive. The design team further reflected upon a wide range of issues and decided that daylight, views and privacy would be compromised in the two building scheme. The one tall building project gradually gained favor.[5] With these new boundary conditions set, Khan reflected upon the implications of such a system and creatively used them to arrive at a novel structure type.[6] To carry the wind loads down to the foundations, conventional tall building systems would not work at this scale. Driven by these limits Khan introduced an innovative system "the braced tube" which he had previously investigated with Goldsmith and Mikio Sasaki, Master of Architecture student at IIT [7]. It was this previous study of the braced tube while teaching at IIT that gave Khan the confidence to put it forward as a solution to the space constraint for the John Hancock Center.

Figure 2

John Hancock Center, Chicago, IL, a braced tube system.

Faced with the challenge of creating systems for ever taller buildings, Khan made use of metaphors. He perceived the new chal-

Figure 3

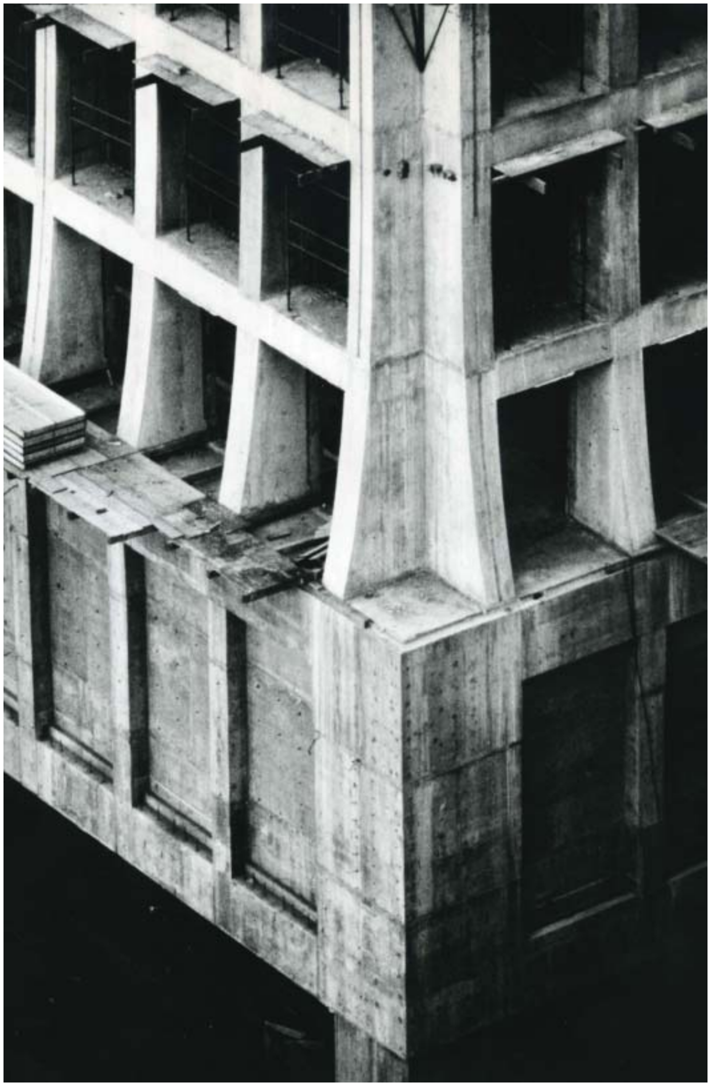
One Shell Plaza, Houston, Texas, a light-weight concrete structure with undulating façades. [image courtesy of Wayman Williams]

lenge to be analogous to another problem already solved. Many inventions and innovations come about by seeing two problems as similar, especially when these problems originate from different domains[8]. For example, for the structural concept behind the Chestnut-Dewitt Apartments system, Khan tried to understand the heart of the structural problem before getting lost in detail. Up to that moment, a typical tall building had a column-beam arrangement with shear walls in the core. The slender nature of the Chestnut-Dewitt Apartments, its height, and the intended architectural program made placing a structural core difficult or inefficient at best.[9] Khan felt that a multi-story building, in general, wants to be a cantilever. In conversation with a colleague he saw the ideal shape for a tall building as a hollow cantilevering "tube" which has high bending and torsional stiffness, ideal for resisting lateral wind loads.[10] He translated this "tube" metaphor into an innovative system for the Chestnut-Dewitt Apartments. The resulting structure has walls on the perimeter only with punched openings for the windows like a perforated tube. All conventional shear walls at the building's core are missing. Khan was perceptive enough to recognize the beneficial effects of three dimensional response of a tube system rather than blindly adhering to the commonly assumed two dimensional behavior which resulted from the prevalent simplified calculation approach for tall buildings at the time.

Khan thought about the structural response as a whole (e.g. cantilevering tube) but also considered every detail. For example, the precursor to the Chestnut-Dewitt Apartments system was the Brunswick Building. Here Khan understood that the columns on the perimeter would be subjected to changing temperatures (based on Chicago climate), where the interior columns and walls would remain at essentially a constant temperature. This leads to differential shortening between the interior and exterior structure. In collaboration with Mark Fintel of the Portland Cement Association, Khan developed an analytical approach and construction details to handle this effect.[11]

Figure 4

Brunswick Building concrete girder under construction, Chicago, Il.



Differential shortening (due to creep and shrinkage) is also a problem when columns carry different loads. This was the design challenge of One Shell Plaza in Houston (Fig. 3). The waffle slab floor framing in the corners of the building plan resulted in uneven distribution of gravity loads in this light-weight concrete building. Shortening of the interior columns close to the shear walls were also prone to differential shortening. Again, this design challenge was studied with Mark Fintel resulting in a procedure to account for differential creep and shrinkage in high rise buildings. As Mark Fintel writes: "Out of this structural solution emerged the visual expression of the elevations: two gentle undulations on each of the four faces of the building, breaking the monotony of the closely spaced columns."[12]

Developing and Manipulating a Toolbox

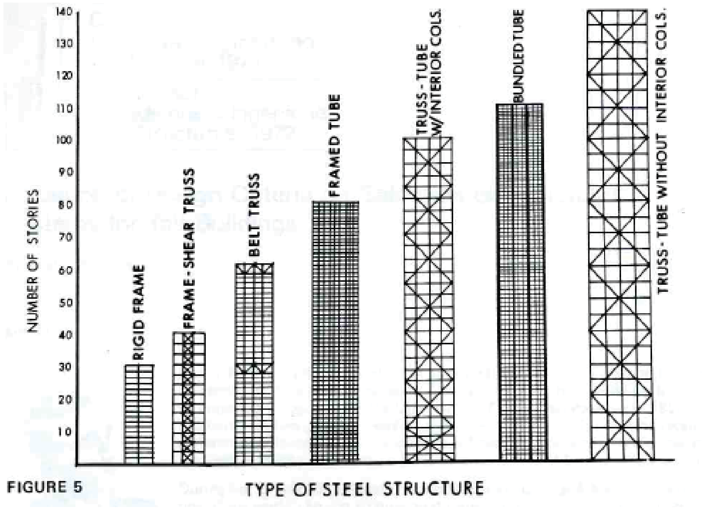
To conceive, advance and realize his projects, Khan developed and manipulated with ease different tools. The aids he chose to use depended upon the challenges he was addressing. We categorize his tools as analytical, physical, 2D and 3D graphical representations, and the written word.

Analytical

Back of the envelope hand calculations and calculations sheets are critical to any engineering design process. With no direct analysis at hand for the calculation of composite action of precast beams and cast-in place slabs for the Route 80, South Entrance project, Khan developed in 1956 a new analytical approach that he laid out on adaptive calculation sheet.[13] He validated his approach with physical load testing. The 1960's saw the advent of large computers and research focus shifted to the development of matrix methods. In his 1967 MIT lecture Khan recognized the utility of the computer as a design tool.[14] In the lecture he elaborated how the design of the John Hancock Center showcased the use of computer in tall building design. For this 100 story high rise project Khan completed the initial computations using in-house developed code.

Figure 5

Khan's sketch of the efficiency of various steel structural systems for various heights. [F.R. Khan 'Influence of Design Criteria on Selection of Structural Systems for Tall Buildings,' *Proceedings of the Canadian Structural Engineering Conference*, Montreal, Canada, (1972): 1-15].



Physical

By proposing novel systems for tall buildings, Khan faced engineering uncertainty. In the design of the Brunswick Building, Khan proposed a 24 feet deep "world's largest concrete girder" (Fig. 4) to transfer the loads of the closely spaced perimeter columns to widely spaced supports at the base. Amongst his engineering peers, questions arose about the structural behavior of such a deep slender girder. To address these concerns he carried out physical experiments on a on twelfth scale model at the Structural Research Laboratory at the University of Illinois[15]. Once the tests were completed, Khan felt confident in using the girder. Throughout his career, Khan carried out physical investigations initiated by questions that arose from challenges in practice. His transformative structural systems became a continuous source for research investigations.

2D and 3D Representations

Excited about expanding the body of knowledge, Khan wanted to share his findings with colleagues. For example, to make maximum use of his investigations of the shear-wall frame interaction system developed for the Brunswick Building, Khan summarized the conclusions in practical visual design charts. These design tools were used for many other preliminary designs of tall buildings. Khan also made a pictorial representation illustrating the efficiency of various structural systems for different heights (Fig. 5).

To clarify his thoughts, Khan meticulously kept little spiral bound notebooks which contained his writing in full sentences and two dimensional sketches (Fig. 6). These sketches complemented his written or spoken word.

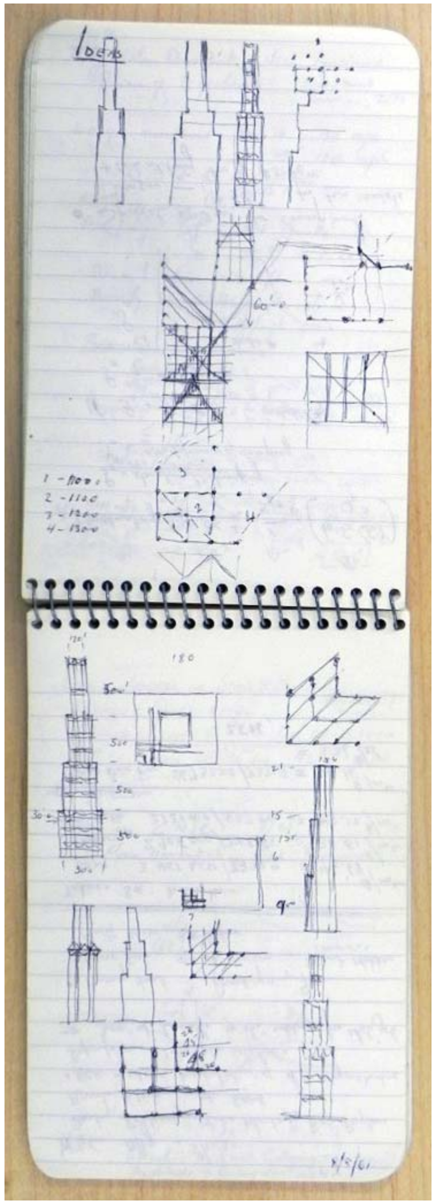
Goldsmith had invited Khan to advise master architecture students at IIT on the structural aspects of their tall building theses in Saturday morning studios. Besides calculations, the theses often culminated in physical architectural models. These models aided the visual and esthetic evaluation of the intended structural expression in three dimensions. In the same spirit, Khan and Bruce Graham evaluated preliminary design models at the SOM office (Fig. 7).

The Written Word

With the development of new structural systems and their associated investigations, Khan wanted to disseminate his findings to peer practitioners and researchers. He often published journal papers or conference proceedings on his projects and on many of the experiments. These papers were valuable to practicing engineers at the time, and even today, some of Khan's studies are relevant for engineering analysis and design. Further, Khan's writings permit us to come to know the engineer himself, his methodologies and approaches to engineering.

Figure 6

Photograph of two of Khan's personal notebooks on exhibition in the Princeton University Engineering Library.

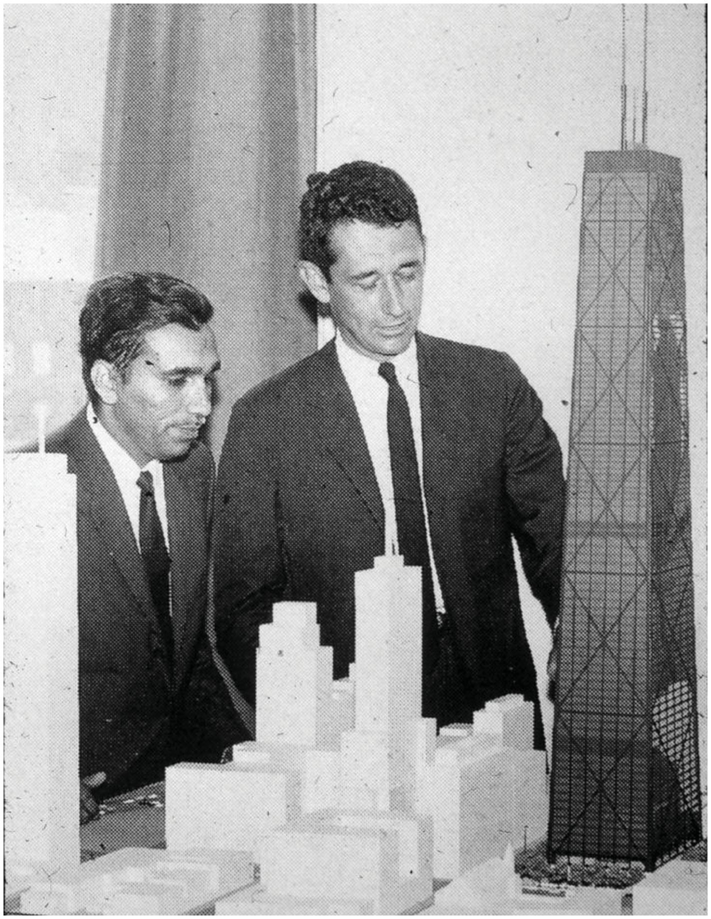


Part 2: The Course "A Social and Multi-Dimensional Exploration of Structures" and Fazlur Khan

In the Fall of 2010, the Princeton CEE department offered for the first time a studio based course (*CEE 463: A Social and Multidimensional Exploration of Structures)* with a site trip. This course focused on the case study of Fazlur Khan. In art, medical and law education, case studies are frequently used to develop knowledge. In engineering education case studies have traditionally been used to describe successful design endeavors and highlight industry best 'practices.'[16, 17] The idea behind studying Khan as a precedent is that our students will later professionally encounter situations, which will not fit Khan's exact context but the students will be able to call upon his engineering approach. Khan was just the vehicle to a broader and deeper teaching of structural design. Through critical reflection upon Khan's methodology and the course assignments, the students started to develop the same toolbox that Khan used in his approach to design.

Figure 7

Khan and Graham with a model of the John Hancock Center.



Pedagogy

Studio education has been central to the US architectural training for most of the 20th and 21st centuries and has proven to be a fruitful model for design education derived from the atelier-based training at the École des Beaux-Arts in 19th century Paris.[18] Our studio's pedagogy which we borrowed from the art/design studio, is based upon the idea that students will learn best those things they have taught themselves when tackling a challenging open-ended assignment. One of the challenges in this course consisted of taking the characteristics of the art/design studio and migrating them towards a research environment. A fundamental requirement for the development of knowledge is that it supports the development of historical scholarship which translated itself in the course as an open-ended assignment. In the CEE 463 course two faculty and one teaching assistant were responsible for 11 senior students. The focus in the studio is on the active learning part by the student. We saw our role as faculty to guide the students.

Within the theme of Fazlur Khan and tall building design, we expected students in groups to focus on one of Khan's most innovative tall buildings and (i) develop and draw conclusions about the innovative structural systems based on back of the envelope calculations combined with numerical engineering analyses, (ii) design, manufacture and assemble a three dimensional scale exhibition model of the building using digital fabrication techniques, (iii) orally present and critique the project in a formal and informal context, (iv) produce photographs and explanatory diagrams that convey the essence of the multi-dimensions of the studied project, (v) through a literature search and a site visit, study the socio-political context of the tall building and (vi) write a15 page text aimed at making the multi dimensions of the chosen design clear to lay people. These six course requirements develop the 'tools' that Khan used to realize his projects as discussed in the previous section. It is important to note that these tools are transferrable to other engineering projects.

We advised the students from the beginning that this course would be different from other engineering classes they had taken. The course details stated: *'Most of the class will involve students working independently in the studio, though we plan to have about 1 to 2 hours of lectures and discussions per week.'* We met twice a week (Tuesday and Thursday) for the three hours in the Structural Models Lab set up as a studio space. Attendance and participa-

Figure 8

Bill Baker (SOM) lectures to our students about the basics of tall building design (left) and is interviewed in the studio (right).

tion of all students was expected and explained. The students were introduced to a phased long term group project. The students grouped themselves in 5 teams of 2 or 3 people. These students knew each other and knew whom they would best work with. Each group focused on one realized tall building design by Khan (Brunswick Building, Sears Tower, John Hancock Center, One Shell Plaza and Two Shell Plaza). For these 5 projects all technical information and research papers were available in the Department's archive: Frank Powell Allen Class of 1881 Reading Room. The course deliverables were a model, a 15 page essay, a tour guide chapter and two oral presentations and critiques. Most of the in-class time was for students to work on their projects. The students were expected to ask us questions. If they did not ask questions, we went around and expected them to answer our questions. We reviewed the students work in small groups. When several teams showed the same difficulty, we held a class discussion.

Invited Speakers

Although the theme was Fazlur Khan, a pedagogical subtheme was tall building design. To this end, we had several invited speakers make an appearance in our course to speak on this topic. These guests included (i) celebrated structural engineers Bill Baker (SOM, Chicago, IL) (Fig. 8), Leslie Robertson (LERA, New York, NY), and Guy Nordenson (Nordenson Associates, New York, NY), (ii) Khan's daughter, Yasmin Sabina Khan, structural engineer and writer, (iii) Professor of structural engineering and structural art critic David Billington, and (iv) Professor of art history, Esther da Costa Meyer. These guests delivered a lecture and/or were interviewed by our students. Most of the interviews were video recorded in a professional studio and can now be viewed as part of the interactive i-pad station at the Fazlur Khan exhibition in the Princeton University Friend Center Engineering Library. The "text" for the course was related to our guests. For example, Yasmin Khan wrote a book about her father, which most students used to develop their work. The other readings were not always

Figure 9

Two students teach the rest of the class (right) about Fazlur Khan's Brunswick Building (left) with its expressed transfer girder above the first floor level.

related to Khan, but related to tall buildings and written by or about the guest as published in magazines or professional papers.

Site Visit

It is rare for a student in civil engineering to visit exemplary works of structural engineering; yet it is expected for a student in architecture or art history to visit the prototypical projects or artifacts that they are studying. Part of the reason that engineers are not making such visits is that they are incorrectly seen by our culture, and even by many in their own profession, as 'technicians' that have no need to experience structures in multiple dimensions. However, these visits are inspiring and instructive beyond anything that is possible in the classroom. Site visits give one a sense of scale that is not possible to fully experience through photographs. One also becomes intimately connected and fully curious about the construction process. The connections are observed up close and the details of bolts and welds that comprise the simple or sometimes complex part of the steel design are seen. For a concrete structure the imprint of the form boards that reminds one that formwork (what molds the concrete) needs to

Figure 10

Visiting with Dan Jadeja from Rosenwasser/Grossman Consulting Engineers in NYC, who worked with Khan on the building in the photo (780 Third Ave.).

Figure 11

Visiting the office of Leslie E. Robertson Associates (Mr. Robertson is in the back center).

be built before the concrete can be poured. During a site visit one can also observe the durability of the structure over time, which is a measure of sustainability. By observing these structures 'in action,' one can measure the success or failure to meet the structure's functionality and one understands the structure's relationship to the community.

Before we embarked upon our 5 day site trip during Fall break, each student had begun their study of one of Khan's buildings through a structural analysis and a investigation of its socio-political context. They summarized their findings in a pocket size travel booklet that was printed and taken on site visits to New York, Chicago and Houston. Before visiting each tall building, the students read the informative text in the travel booklet. On site, each student team explained "their" tall building: its structural significance and construction process and its socio-political context to the rest of the class (Fig. 9). During these visits, all students studied carefully the structure, its details, its surroundings, how it had weathered over time, any adaptations that had been made to it, and its relationship to the community.

On our site trip, we were given private tours of several buildings. In New York we toured the Bank of America Tower (by Severud Associates), New York Times Building (by Thornton Tomasetti), 780 Third Avenue (by Khan consulting with Rosenwasser/Grossman), and Times Square Tower (by Thornton Tomasetti). Not all buildings were exclusively designed by Khan; visiting related recent and older tall buildings gave the students the opportunity to put Khan's designs in a historic-technological perspective. In Chicago we were given private tours of Khan's Chestnut DeWitt Apartments and the John Hancock Center. And finally in Houston, we were guided through many levels of One Shell Plaza Two Shell Plaza designed by Khan. On these tours, our hosts gave us access to restricted areas, removed interior elements to show us the structural system and provided valuable engineering and building management information.

Our students also visited consulting structural engineering firms. In New York City, the engineer who worked with Khan on 780 Third Avenue gave us a presentation about the building (while being in the building) and reflected on his experience working with Khan (Fig. 10). We also went to the offices of Severud Associates, Thornton Tomasetti, and Leslie E. Robertson Associates (Fig. 11). In Chicago we visited SOM. At all of these firms, practicing engineers gave us a tour of their office, presentations of important projects that they have worked on, and shared advice to our students about their education and career. Based on the student feedback, the site visit was a very valuable experience in many

Figure 12

One group of students assembles the model of the One Shell Plaza from laser cut panels in the studio space.

personal and professional ways (discussed in more detail in the next section). Many students had never been to engineering offices before. By visiting and talking to practicing engineers, a seed was planted of where their professional career might be heading. Encouraged by those encounters, a number of our students applied to graduate school, an option some had not considered prior to the trip.

Models and Exhibition

One of our course objectives is to learn to consider the constructability aspects of design through the process of model building (Fig. 12). Through this hands on experience the students learn that what they design on 2D paper needs to be constructible in 3D. This observation seems obvious but unfortunately often conceived designs cannot be built or their construction process is so complex that the project becomes too expensive. The models (as in any real structure) should be well-crafted and suited for exhibition display.

The five models (Sears Tower, John Hancock Center, Brunswick Building, One Shell Plaza and Two Shell Plaza) are currently on display as part of an exhibition 'Fazlur Khan: Structural Artist of Urban Building Forms' at the entrance lobby of Princeton University's Engineering Library at the Friend Center (Fig. 13). Through the juxtaposition of the 3D scale models, photographs, and explanatory panels that illustrate the relationship between forces and form, visitors to the exhibition experience the process of Khan's innovative structural engineering design. An interactive ipad station plays the interviews made by the students with the special guests as well as two documentaries about the Sears Tower and the John Hancock Center. The librarian has reported to us that the ipad station (which only provides access to material related to the exhibition) is continuously used, that students often stop to look at the models and wall mounts, and that tours of Princeton's School of Engineering and Applied Science to potential students and their families now pass through this exhibition. So even though our course was designed for a dozen students, it continues to "teach" countless more.

Website and Book

Based on the contents of the essays written by the students, we developed an educational website on Fazlur Khan, his works, the exhibition, and the course (khan.princeton.edu). The website material forms most of the content of the exhibition's ipad station. Freely accessible on the internet, the webpages are a source of information for anyone interested in the subject, and are also used in another course, CEE262 'Structures in the Urban Environment'. Therefore, like the exhibition, through this digital platform we continue to teach many more beyond the traditional classroom setting. In the near future, and with David Billington, we hope to use this in-depth study of Khan and his work carried out by the students to write a book on Fazlur Khan in the same spirit as David Billington's other seminal recent books such as *The Art of Structural Design: A Swiss Legacy*[19] and *Felix Candela: Engineer, Builder, Structural Artist*.[20]

Figure 13

Fazlur Khan, artist of urban building forms, exhibition in the Friend Center Engineering Library.

Impact of Course on Effectiveness of Teaching and Student Learning

We believe that the studio method we employed in the course is effective in developing the students' skills in writing, model making, drawing, engineering calculations, and spoken and written communication. Because of the nature of the course objectives, the evaluation of the course's effectiveness is qualitative and difficult to measure (and no similar course has ever been run in our department before). We support our findings with the students' reactions to this studio based learning which were captured in the course evaluations.

Despite the fact that the studio is a radical change from traditional classroom teaching, the students' reactions were positive: *'Overall, this was an excellent course. It incorporated many interesting and exciting aspects that contributed to my (and other students') learning in several ways.'*

Negative comments were related to the duration the project: '*... I wish we had been given a bit more time to work on [the project].*'

Another wrote: *'This class was a lot of fun, but it was also A LOT of work. I think a lot of the stress that came out of this class was due to the fast pacing at the end, which was mostly a result of us not realizing how long it would actually take to build the models and write a thorough report.'*

Because the students are unfamiliar with this studio teaching format, we see that in the future we must take care to reassure students regarding expectations. Some students wanted more assistance and help than the studio offered: *'It was heavily independent research and work based, and I think we could have learned more if we were taught more.'* The studio model confused some students as to the evaluation procedure. In the future we will be clearer about expected student performance: *'Expectations were sometimes unclear.'*

The students wrote texts that with little adaptation became part of a website and with more work can become book chapters for a general audience. The text contains the results of complex engineering analysis, presented to be easily understood. One student commented '*I think we were well prepared for the written work,* *and that the comments in response to the written work were very helpful and showed that the work had been critically reviewed.'*

We think that the study trip will have a large impact on the professional development of our students. During that trip we visited several engineering design offices whose engineers were encouraging our students to go to graduate school, an option they had until then not really seriously considered. The students saw what the day-to-day job of a practicing engineer involves and started to imagine themselves in those positions. Some relevant comments include:*'The trip has to be the highlight of the course.'* , *'I've definitely taken a lot from the course in terms of thinking about structural engineering on a practical level.'* and ,*'It was inspiring to meet several well-known people in the field of structural engineering, and to hear their perspective on Fazlur Khan and tall buildings. The trip was very interesting and inspiring, but rather hectic.'*

The students enjoyed the oral presentations on site, which were of very high quality – on the site trip people walking by would stop to listen to their presentations: *'I liked having the presentations so each group could learn about the other buildings.'*

The models are beautifully crafted (and this coming from students who have never built models before) and are of exhibition quality. This activity taught the students a new skill of using digital fabrication techniques (the laser cutter). A typical response about that exercise was *'...building the model was a phenomenal exercise--both challenging and rewarding.'*

Transferrability of the Course to Different Educational Contexts

The foundation of the presented pilot course has the potential to scale well to various educational settings (larger classes, no room for electives, no finances for site trip) with a number of adjustments.

For larger classes with no dedicated studio space available, the students could be organized to have formal short critiques with feedback from the faculty at set times instead of the faculty wandering around in the studio and being available at all times. In other courses we have also experimented with group/peer critiques and peer assessments as a means to provide regular feedback on the progress and the final results of the presented work.

Most engineering curricula are overloaded leaving no room for additional electives. The historical scholarship could be reduced in scope and incorporated as an assignment in existing base courses like Mechanics of Solids, Statics, Concrete and Steel Design. Not only are most curricula overloaded, but typically so are the instructors. Note that the two faculty were sharing the responsibility of this course since it was done in addition to the regular teaching load – on a volunteer basis. One faculty could easily handle it. Knowing now how to deliver this course, most/much of the preparation can be done in advance before the semester begins. The teaching assistant was most valuable for arranging the site visits, but the large majority of the other work was done by the faculty. For the site trip, we foresee how local trips to important structures and engineering practices could give the students a sense of scale, three and four dimensionality (durability – time aspect) and make them envisage where their professional careers may take them.

Conclusion

In this paper we focused on the structural artist Fazlur Khan and how students can learn successful approaches to engineering by studying his approach to structural design and innovations The first part of the paper focused on Khan as a designer, teacher, and scholar. By practicing as a structural engineer for tall buildings, Khan discovered continuously new challenges which he set out to solve. By critically reflecting upon the unknown engineering aspects in his tall building projects and by drawing upon his own investigation, he greatly advanced tall building design.

In the second part of the paper we turned our focus to the CEE463 course '*A social and multi-dimensional exploration of structures*'. Through a detailed study of Fazlur Khan's works, the course has the pedagogical objectives of the spatial relations of dimensions and time (sustainability and society). It develops the student's skills in communication of complex technical matters with peers and laymen, cultivates spoken, written, pictorial, analytical and numerical competence, and encourages critical reflection on social, political, historic influences. During the course the students had the opportunity to visit many of Khan's structures and other important tall buildings, meet (and interview) with the leading figures and critics in current tall building construction, interact with practicing structural engineers, reach out to the large CEE 262 'Structures in the Urban Environment' class and the general public by displaying their models in the Khan exhibition at Princeton's Engineering library, develop the associated website, and contribute to the first draft of a book chapter. Overall, student evaluations of the course were positive. We learned that some students were not comfortable in an independent learning studio-style setting, which is not common in engineering education. We believe that the exhibition and website that developed from this course will continue to teach many more about Fazlur Khan so this course has a broad impact.

The development of this course was heavily influenced by the scholarship and teachings of David. For almost 40 years, he has taught a course that focuses on fourteen 'structural artists' who created elegant structures that were disciplined by efficiency and economy and "at the heart of technology, they found their own individuality; they created personal styles without denying any of the rigor of engineering." Our new course takes a zoom lens to one of those structural artists. We are grateful to David for inspiring us to teach this course because such education is crucial for the future of structural art; and in studying it, educators, practitioners, and the general public can recognize the potential for this new art form in the 21st century.

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NEXT GENERATION STRUCTURAL DESIGN
Challenges and Chances

Annette Bögle

Challenges

Regarding today's built environment an increasing rationalized planning of manifold engineering structures like roofs, buildings, stations or bridges can be noticed, whereas in the planning and the design process the individual boundary conditions defined by the environmental, economic, political and social context are often mostly neglected. Taking an aesthetical and social point of view these structures seldom are satisfying. Blaming the hard economic times, the boundary conditions, "crazy" architects, the builder or some officials and their rules and standards is a natural reflex but it is also only half of the truth. Foremost, we engineers are responsible for this development ourselves - by writing our own standards and regulations, by interpreting them and most importantly by teaching them to young engineers and students by lecture or living example in schools and universities, in companies and institutions. This is due to the fact that during the last decades civil and structural engineers have focused unilaterally on the rational-analytic aspect of their area of responsibility and have therefore lost sight of their real and original area of activity, which arises in a mixture of logical and empirical knowledge.

This goes along with the usual separation of today's architecture into an aesthetical-creative and a technical-analytical part, the last one treated synonymic to engineering. Only few connect the careful shaped, slender and elegant shaft of a television tower or the well-formed abutment of a bridge with the creativity and personality of an engineer. In fact, engineering is associated predominantly with the qualities of rationality, computability, technocracy and reproducibility. It is representing the technical-analytical side of architecture and acts as a kind of antipode to art as a unique, innovative, creative and emotional activity. On the other hand, purposeless artistic creating counts today as an expression of personality and posture of the artist. While the purpose-directed engineer's science in contrast seems to fulfill apparently objective requirements, creativity is not connected at all with the analytical methods in engineering.

This matter deserves even more attention when we realize the enormous challenges our society in general and engineering in particular need to face today. New materials and new digital tools enable new solutions but also demand a new way of engineering. In a broader sense this is influenced also by globalization with new ways of communication and the decentralization of the workflow. Also, changes in social life, the demographic development and the climatic change demand new, sustainable solutions in engineering.

Today's situation in engineering is not satisfying, either for society – who wants to have technical, functional and aesthetical satisfying structures – or for the engineers themselves, who are uprooted from part of their original way of working.[1] To generate innovative and sustainable answers for today's challenges a substantial change in engineering practice as well as education becomes indispensable. The needed paradigm shift has to bring back creativity into all aspects of the engineering work. Therefore a heightened awareness of engineering design as well as a "science" of design in engineering becomes necessary. A theory of design in engineering deals with the ideal aspects of engineering which will include all aspects of the structure (dependencies of form, material, functionality) and the design process (dependencies of time, skills, knowledge, personality).

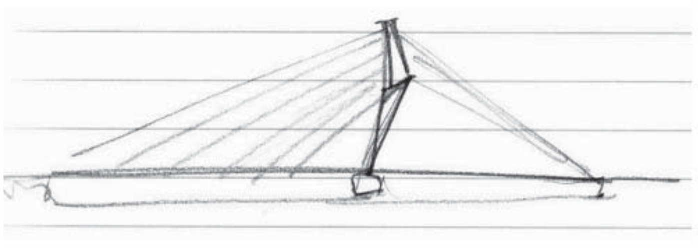
In architecture, it is self-evident that history and theory of architecture are vital fields of academic research and teaching. It is understood that without a critical review of the profession and work any qualitative improvement in architecture would be inconceivable.

New Concept in Teaching Engineering

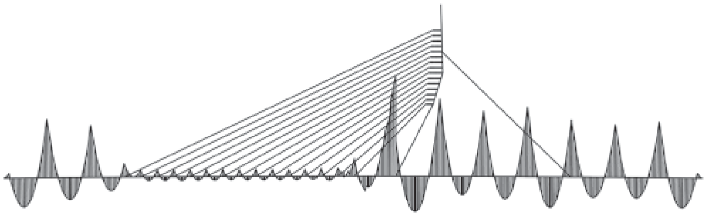
As different societies generate different cultures this also enfolds different educational approaches to structural design. For example, in Germany there always has been a close interlink between structural design classes at universities and practical experience. So most professors of structural design who receive the

Figure 1

The process of conceptual and structural design [Schlaich 2006, Bögle and Schlaich 2010].

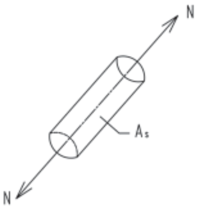


Conceiving

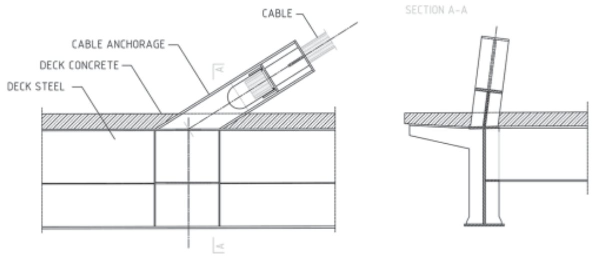


Modeling

Backstay cables	Max N [kN]	Working stress [MPa]	No. of strands (A=150mm² each)
1	13820,00	725,46	127
2	13439,00	705,46	127
3	11185,00	684,10	109
4	10755,00	657,80	109



Dimensioning



Detailing

call of full professorship have their own office (and mostly keep it) or have at least years of practical experience in a prominent role. The great advantage of this tradition is a closeness of teaching to actual engineering practice. Thus Mike Schlaich at TU Berlin could develop his very practical oriented steps of the process of conceptual and structural design (Fig. 1).[2] This is one of the first concepts in German structural design that interlinks the process of conceiving and the process of detailing with both modeling and dimensioning. Certainly, this interlink of praxis and education has to take intensive attention to theoretical reflection and different pedagogical approaches.

While *modeling and dimensioning* belong to the traditional core competence of engineers, and while *detailing* constitutes very much the connection between the academic curriculum and the practical work, the most complex - and strange in today's typical engineering eye - is the first one: *conceiving*. Creating the overall concept is a creative process, which includes all the typical characteristics of processes: chaotic and uncertain, not reproducible nor predictable. And neither the engineering practice nor the education deals with this sufficiently at the moment.

But luckily, more and more engineers in academia as well as in practice realize that a reorientation in education has become necessary and several concepts have been developed and discussed.[3] These concepts have in common that they have started to change the academic curriculum in terms of both method and content. Both are necessary to prepare engineering students for the actual challenges of their profession. The actual discussion in Germany is rooted in the so called "Dortmunder Modell Bauwesen" at the University of Dortmund by Stefan Polóny[4] as well as in the introduction of the material comprehensive teaching at the University of Stuttgart by Jörg Schlaich.[5] Both concepts do not claim to be the one and only solution, but they have proven to be suitable to generate a new awareness concerning conceptual design and to start up the necessary development. The integrated education in Dortmund pledges all architects and engineers involved in the design and building process to be educated together and to constant communication. The education is project orientated in contrast to more common head-on classes. Thus the students get a more active role in education, and active learning is a much more sustainable way of gaining knowledge.[6] In Stuttgart, Jörg Schlaich was influenced by his experiences through his engineering practice: never does a client 'order' a steel, concrete or wooden bridge, he desires to get a good bridge which suits the context. Thus Schlaich claimed to annul the traditional material orientated classes and established the first material comprehensive teaching in structural engineering, completed by including the process of design into the engineering education. In many lectures Jörg Schlaich proclaims that the art of building is not divisible and therefore engineering should never focus only on its technical aspects but also has to take into account aesthetical and functional aspects.[7]

Basics of Creativity

The proposed new methodical approach in education shows how basic principles as prerequisites for creativity can be taught. These principles serve to awaken the innate creativity of each human being. But of course, as creativity depends on human beings, there is the very individual – irrational – part which can never be taught, and that is not accessible with rational arguments.[8]

To work out principles for creativity in engineering design the first, most evident step is to train perception and to study how perception is working. Based on this knowledge the second very helpful step is to look into history, where different design approaches arise. Thirdly engineers need to be capable of (constructive) criticism so that they may review and critique their own and other engineers' work. Last but not least, engineers should deal with the process of designing, and with this knowledge they will be able to create own designs. The following section shows why these aspects can encourage the development of creative structural design.

Thereby, it is self-evident that the so called hard facts (mathematics, mechanics, physics, etc.) are an essential part of the basics of creativity. Only if engineers know for example how to formulate and solve aerodynamic problems are they able to develop new solutions for slender towers or long-span bridges. But as these classical theoretical approaches are already positioned in the actual curriculum, they will not be further discussed here. It should be noted also that even if the actual curriculum has to change, these elements never ever should disappear.

Look and Listen – Training of Perception

Perception is the prerequisite to meet the context of a structure and to perceive the structure itself. It is based on human experience and depends on knowledge, abilities and the point of view (Fig. 2, 3). The context of the structure is built by its social, cultural and topographical environment. The structure itself can be described by its appearance, material, form and dimensions. It is essential that perception should not be reduced to the visual aspect; instead it has to meet all senses. Thus the haptic quality of a structure, particularly of its surface has an essential influence on the effect of a building and its perception. Like designing, perception has process-related features - perception appears to be chaotic, complex and non-linear. But just these characteristics enable a flash of intuition: well known facts will be joined by spontaneous and novel ones. In education, perception has to be experienced (Fig. 4): students should be trained in studying real structures and they should learn about different structural approaches. Therefore, excursions have to be an essential element in teaching.

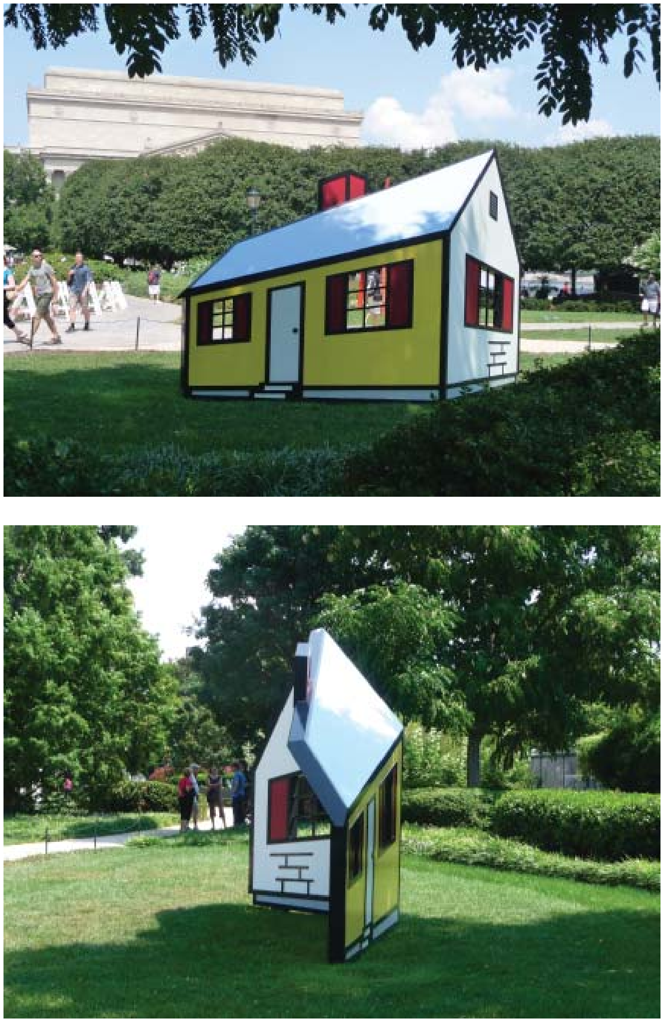
The process of perception has to be explored and trained in education: real buildings, their structure and their context should be analyzed and different structural solutions detected; excursions to buildings and building sites are one possibility. Thus the inspection of the Zarzuela Hippodrome of Eduardo Torroja in

Figure 2

Children exploring the Cloud Gate, Millenium Park, Chicago, USA 2006.
Artist: Anish Kapoor, Engineer: Atelier One.

Figure 3

Roy Lichtenstein, House I, 1996/98, Hirschhorn Museum, Washington DC, USA



Madrid left a more sustainable impression than just the analysis of a picture or drawing (Fig. 4). Most important is also to meet other practicing engineers and discuss their opinions. For example, in 2006 on our tour through Switzerland, Jürg Conzett explained his own personal attitude concerning the art of engineering (Fig. 5). These experiences allow the students to learn about different points of view in engineering as well as to develop their own opinion.

Figure 4

Students of the TU Berlin exploring structural history, 2006: Zarzuela Hippodrome, Madrid, Spain, 1935.

Figure 5

Jürg Conzett in conversation with students from the TU Berlin, 2005.

Discover and Research – Structural History

Structural history in the context of this paper serves as an essential key to enhance creativity and last but not least to enlarge the quality of our built environment. Focusing on the whole development of structures, starting with the first simple building activities, also the actual developments in structural engineering should be made an issue. Knowing about history is of fundamental importance. Asked for their favored engineer or structure most first year students do not know any answer. In the best case they can name so called star-architects and their modern landmark projects. Even after several semesters at the university it's hard to find students knowing names like John August Roebling, Thomas Telford, Gustav Eiffel, Robert Maillart, Vladimir Suchov, Eduardo Torroja, Felix Candela or Fritz Leonhardt. Can you imagine music students not knowing Johann Sebastian Bach, philosophy students not knowing Emanuel Kant or literature students who never heard of William Shakespeare?

Firstly the clearest and self-evident advantage of structural history is that in history the boundary conditions of conceptual design, focusing on the dependencies of form, structure, material and construction, become obvious. Depending on time, knowledge and possibilities of the building society, only specific structural solutions can arise. Vice versa, historic structures become only readable if these boundary conditions are studied. Therewith, a deep understanding of the different, complex and time dependent boundary conditions arises. It becomes obvious that at a different time, in a different situation and with different people, the resulting structures are different too. This enables one aim of studying and teaching structural history: the transfer of the knowledge about the uniqueness and time dependency of boundary conditions into the actual discussion about the design of engineering structures.

For example, at the time of building the Pantheon it was the spiritual wish to create a space, covered by a hemisphere; it was even possible to inscribe a whole sphere into this building. But from the outside this ideal form and its spiritual perfection is not visual. This is an example for form determination; here the designer and builders had the wish to realize a specific form, but they had only stone and mortar for realization. Their material properties determined a specific structural performance but it is just not possible to build a structural hemisphere with these materials only. To achieve a hemisphere in the interior, a statically plane shell with

Figure 6

Pantheon, Rome, 118-125 (left) [archive schlaich bergermann und partner, Stuttgart]; Olympic Roof, Munich, Germany, 1972 (middle) [Bögle et al. 2003]; Guggenheim Museum Bilbao, Spain, 1997 (right).

increasing thickness was realized; the visual hemispherical form is not the static form. This example enables us to realize, that not everything was and is buildable; in history the boundary conditions of what was possible were quite strict. However, structural history shows us how compromises were made; the knowledge and the values of the building society determine how the interdependency of form and structure is expressed.

Going on in history and focusing on the relation between structure and form further developments become obvious: The advancing sociopolitical enlightenment and the progress in science and technology obscured the unambiguous relation between form and structure. This creates the freedom to prefer certain aspects. Similar to the separation of art and technology the trends towards form-setting and form-finding emerge. Form-setting focuses on form as an expression of the human desire to design – this was applied expressively in the case of the Guggenheim Museum in Bilbao. Form-finding focuses on form as an efficient technological object; a leading example is the Olympic roof in Munich. These short examples serve to show the relation between form, structure, material and function (Fig. 6).

But structural history can even go a step further; it also shows the passion and the intention of the people behind the designs. Particularly whenever a new technology or material came up the designers and builders explored with courage and creativity the borders of the limits. All major developments in structural engineering can serve as examples for this. If we accept the personal

influence of the designer on the development of a structure, it is most logical also to realize the cultural influence. This is also one of the reasons for different design approaches, visible in different structural styles, or in different calculation and dimensioning approaches. For example the development of concert shells starting after the 1920s in Germany lead to mathematical-analytical forms, in Italy we can study an historical and artistic approach, and in Spain the new structural forms were rooted in the artisan building tradition.[9]

The aim of structural history must be to transfer the gained knowledge about structures into the actual building culture. For example, studying the shells of Felix Candela not only enables students to understand the behavior of the hyperbolic shells, but also enables them to transfer this knowledge to modern cable net structures and grid shells.[10] This is how structural history encourages young structural engineers to search for their own innovative, unique and creative structural solutions for unique situations. The curriculum should change to give space for these topics. Preferably at the beginning of the academic education, a course about the principles of structures in combination with the development of structures should be placed. This course should guide the students in perceiving the structures and their boundary conditions (see section "Look and Listen"). Students should study specific structures, write an essay and present the results, for example by creating an exhibition. Excursions also are an essential element to learn about and from historic structures. And last but not least students can explore relations between form and

Figure 7

Bridge in Vitoria, Spain, 2007. Engineer: pedelta, Juan Sobrino.

structural behavior by building models from existing historic structures.[11]

Discuss and Criticize – Culture of Critique

Critique is a wide philosophical field. Hence, in the context of this paper, and just like its Greek roots indicate, critique can be briefly specified as the art of judgment and examination. The aim of critique is the detection of a mistake and the protection from pretension and deception. Thus critique is essential to generate a personal opinion and to find a position concerning specific topics. But actually our attitude concerning critique is ambivalent. As much as everybody insists on his own opinion and judgment, he does not want his projects to be criticized by others. But how does anyone get to a well-balanced opinion if not by using the methods of critique?

In other disciplines like in architecture as well as in mechanical engineering, for example, the culture of critique is well established as an essential element of creative practice. The search for and the critique of solutions belong to the most important, always recurring working steps thus providing information about how a solution fulfils the requirements and how it deals with given boundary conditions. In the process of criticism, all aspects of the solution have to be named, including all negative as well as all positive aspects, with the aim to detect problems and mistakes. Thus, critique is part of creative thinking and working.

Critique is important during the whole design process, and is part of the evaluation process which is necessary to bring a design from the status of an idea to a real structure. Design critique allows one to re-think and to learn to discuss about structural problems and solutions. Students could take their own projects as well as already finished ones and discuss them from different points of view. Then design critique can become a prerequisite for generating and strengthening one's position concerning structural engineering, and increase its overall quality.

The open view and the critical questioning of decisions finally allow the examination of the question, what actually is meant by the term "The Art of Structural Design". Here, the discussion should not only focus on established arguments like a load-efficient design language "Form Follows Force". There are far more diverging approaches. Therefore, it is required of engineers - in terms of their creative work – to make themselves familiar with other design languages and to learn to criticize them - especially considering the potential of modern technology.

Thus it is possible to discuss and criticize different design approaches using very contrasting solutions in lectures or seminars like the example of the strikingly shaped bridge in Vitoria, Spain (Fig. 7), which is much debated and very controversial. And the old question arises anew: "Shall we do everything that we can do?" The shape of its supports is only possible thanks to modern production techniques and obviously contradicts a load-efficient design language. On the other hand the structural design of the Rostock Bridge (Fig. 8) reflects the flow of force in the structure and thus continues the "classical" principle of the art of structural engineering. These different positions are comparable and should be critically discussed. Also the internet, with its numerous

Figure 8

Bridge in Pforzheim, Germany, 1992. Engineer: Schlaich, Bergermann und Partner.

discussion forums and blogs is an invitation to practice criticism, "The Happy pontist" (http://happypontist.blogspot.com/) shall be mentioned here (as one of many examples).

Design and Withdraw – Process of Designing

The aim of a design process in engineering is to create a structural form; preferably this process is target-oriented to solve a specific structural task. It is hard to rationally describe where this process starts and where it ends. Designing happens in the polar areas of social convention and physiological relations, of experience and action, of intuition and knowledge. Here, human experience is linked with the inner human make-up. Ideas are sketched and rejected again. Going beyond the standard approaches creates variety. But closure is necessary to formulate the ideas and permit action. Therefore, a process of selecting occurs parallel to the design process. The past – such as intuitive experience – is intertwined with present knowledge. Thus, irrational and subconscious relations are linked with rational and logical dependencies. Consequently it is impossible to determine the basis and the result of the design process. For the design process, this has the consequence of uncertainty and risk, and the usual academic curriculum does not prepare engineering students with the abilities to deal with such processes. Therefore, design projects have to be an essential part of the education as well as the elements of designing like sketching, dealing with the design process and with the elements of design.

When the focus of designing is directed to a constructive task, the internal dialectic of the design process is revealed. Here the typical aspects of the design process face the requirements imposed by the planning sequence: Although the chaotic, complex and conflicting design process thrives on spontaneous ideas, an orderly planning sequence demands linearity and unambiguity to ensure an efficient performance. This dialectic cannot be rescinded; on the contrary the methodical approach of morphology may lead to its acceptance. Thus a process of selection and evaluation occurs parallel to the formation of an idea. In the language of the theory of self-organization, this corresponds to the processes of opening and closing. And vice versa it shows how the process of evaluation interlinks designing with materializing.

Dealing with this process needs to be learned - project work and design seminars serve this purpose. Two important findings should be highlighted here for the students: First, it is a process in which one cannot have complete knowledge or control. Second, the result is not explicit. There is no right or wrong solution, but an optimized compromise of the complex singular boundary conditions of a particular design situation. Whether the solution, the chosen design, is a "right" solution becomes evident only in hindsight. Therefore, it is even more necessary to handle the design task as responsible as possible.

The usual academic curriculum is often not sufficient to prepare students of engineering sciences to deal with the processes described here. Therefore, design projects need to be essential components of engineering education, as well as the individual elements of design, such as sketching or a capable dealing with criticism. The same applies of course for the detailing of structures. The four aspects just under discussion need to be applied also to the details and connections of the structure. Furthermore, the structural design is based on a solid mathematical and scientific foundation, resulting in special conditions for teaching.

Outlook

To meet today's challenges in engineering, a radical paradigm shift becomes necessary and a new concept in teaching can be an essential part of it. This paper shows principles and basic elements being suitable for the essential change in the academic curriculum in particular, as well as for a shift towards a conceptual approach in engineering design in general. Part of these changes is the development of a theory of design in engineering - something that is common in architecture and any other design discipline, but not in structural engineering. A theory of design serves as a critical approach towards the built environment and its structures. It includes all aspects of the structure and its design process, thus it enables a judgment about the structure, its suitability and its sustainability, not only in an ecological but also in a structural sense. Overall, the implementation of these considerations enables engineers to design next generation structures.

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A HISTORICAL PERSPECTIVE ON SUSPENSION BRIDGES
Design vs. Analysis and the Work of John A. Roebling

Stephen G. Buonopane

Introduction

The research and teaching of David Billington is ground-breaking in envisioning structural art as a balance of the scientific, social, and symbolic. This paper primarily explores the scientific aspect of structural engineering and uses the history of suspension bridges to contrast two approaches to structural engineering—design vs. analysis. Structural *design* applies three basic principles of strength, redundancy and ductility to achieve safe and serviceable structures. Structural *analysis* quantifies response of a particular structure subjected to particular loads and boundary conditions. Analysis is one tool in the process of structural engineering, but is distinct from design. The 20th century has been largely dominated by an analysis-based approach which is embodied in our profession's numerous prescriptive design codes and specifications. The reemergence of performance-based structural engineering has initiated a return towards the design-based approach. However, the fundamental elements of performance-based engineering can be found in 19th century engineering practice, prior to the advent of modern structural analysis. The evolution from design-based to analysis-based structural engineering is well illustrated by the history of suspension bridges. Further, the elements of a design-based approach to engineering transcend the field of structural engineering and are an active research area in other fields which involve complex systems and networks.

Any successful structure must possess sufficient *strength* or capacity to support all possible loads, including some factor of safety to account for lack of knowledge, uncertainty and variability. *Redundancy* in a structure provides multiple load paths should one load path lose the ability to carry additional load or fail entirely. *Ductility*, or load sharing, is required for a structure to be able to transfer load between sub-systems or load paths, especially as certain load paths become limited in capacity or fail. The characteristics of strength, redundancy and ductility defined in this manner are fundamental principles of structural *design*. These engineering design objectives are not limited to the field of structural engineering, but are also relevant to the engineering of other complex systems, such as communication or power transmission networks. For example a transmission network must have sufficient total capacity to meet demand, including some safety factor. The network must have redundancy—multiple routes over which information can be transmitted between any two points. And the network must have ductility—the ability to re-route information should one branch of the network fail. The behavior of complex networks, including the study of failure, reliability, resilience and robustness, is a highly active research area that spans across numerous disciplines.[1]

Viewed through the lens of modern structural analysis, many 19th century bridges appear to have unusual structural forms and complex load paths. However, such bridges were designed primarily with empirical techniques or rules-of-thumb, without the need to confine their structural form within the mathematical framework of structural analysis. Modern analysis of indeterminate structures has its roots in the 19th century in the work of Navier, who provided a methodology for the solution of indeterminate structures by combining equilibrium and deformation equations.[2] For structures that were highly indeterminate, the practical solution of the resulting large system of simultaneous equations limited the application of Navier's methods. Highly indeterminate structures continued to be designed by approximate methods well into the 20th century.

The advent of mathematical structural analysis would ultimately have the effect of constricting the space of possible designs to those that could be analyzed with the existing methods. The ability to mathematically analyze a structure can provide a false sense of certainty that the structure will in fact behave in the manner predicted. This conflict between design and analysis has been previously explored by Jacques Heyman, who coined the term "Navier's straightjacket" to describe the constricting influence of analysis on design.[3] Research of structures engineered from a design-based approach outside of "Navier's straightjacket" can still provide fundamental insights into structural behavior that remain valid even today.

History of Suspension Bridge Design

Suspension bridges provide a rich historical and technical case study of the interaction between design and analysis in structural engineering. In parallel with the development of mathematical structural analysis during the 19th century, suspension bridges evolved from primitive structures spanning a few hundred feet to highly engineered structures spanning thousands of feet. A suspension bridge has a simple structural form providing a close correspondence between mathematical theory and practical object. A hanging cable is a nearly pure physical expression of theoretical engineering mechanics, and at the same time provides the structural system for an entirely functional, albeit unstiffened, suspension bridge. The theory of a deck-stiffened suspension bridge need be only one degree indeterminate, although formulated as a system of fairly complex, non-linear integral and differential equations.

The defining structural design problem of suspension bridges is control of vertical motions from live loads and wind loads. The development and performance of suspension bridges reveal two distinct periods in which suspension bridges were susceptible to wind-induced motions with some bridges being destroyed and others retrofit with additional stiffening (Figure 1). Initial success in preventing wind-induced motions did not emerge from the mathematical analysis of suspension bridges, but rather from a structural design approach grounded in fundamental principles of strength, redundancy and ductility, and supplemented with close observation of the behavior of existing bridges. For nearly all of the 19th century, structural design of suspension bridges far surpassed the analytical capabilities of structural analysis, particularly for live and wind loads. In fact, the success of actual suspension bridge designs led to advancements in analysis methods, which would in turn influence the form of the next generation of suspension bridges.

At the focal point of this interaction of design and analysis is the career of John A. Roebling (1806-1869), the preeminent suspension bridge designer of the 19th century. John A. Roebling designed several of the most significant and longest spanning suspension bridges of the 19th century, including the Niagara Railroad Bridge (1855), the Cincinnati and Covington Bridge (1867) and the East River (or Brooklyn) Bridge (1883), none of which suffered from excessive motion due to live loads or wind. Roebling superimposed three structural systems—suspension cable, diagonal stays and stiffening truss—creating a structural form that was highly indeterminate. With only the the theory of the unstiffened suspension cable available, Roebling could not use structural analysis in the modern sense to calculate the distribution of forces within his bridges. Instead, Roebling developed a rational engineering design approach which could be applied to an extremely complex structural form to produce safe and serviceable bridges of record length and load-carrying capacity. Roebling's own writings and calculations demonstrate his understanding and application of the fundamental structural design principles of strength, redundancy and ductility. Roebling's seemingly complex structural system becomes transparent when viewed from the perspective of structural *design*, rather than from that of structural *analysis*.

The success of Roebling's bridges inspired others to develop the mathematical tools to analyze deck-stiffened bridges, but not until the Williamsburg Bridge (1903) would a bridge designed on the basis of structural analysis surpass the Brooklyn Bridge in length of main span, and then only by a mere 5 feet. In the early 20th century the new mathematical theory of suspension bridges confined structural engineering of suspension bridges within Navier's straightjacket and contributed to the reemergence of the excessive wind-induced motions punctuated by the dramatic collapse of the Tacoma Narrows Bridge in 1940.

This essay is divided into three main parts. The first part reviews the design and performance of early 19th century suspension bridges, including the theory of the unstiffened suspension cable. The focus is on understanding how the ability to perform analysis of an unstiffened suspension cable affected the design of suspen-

Figure 1

Evolution of longest suspension bridge span and performance of suspension bridges under wind forces.

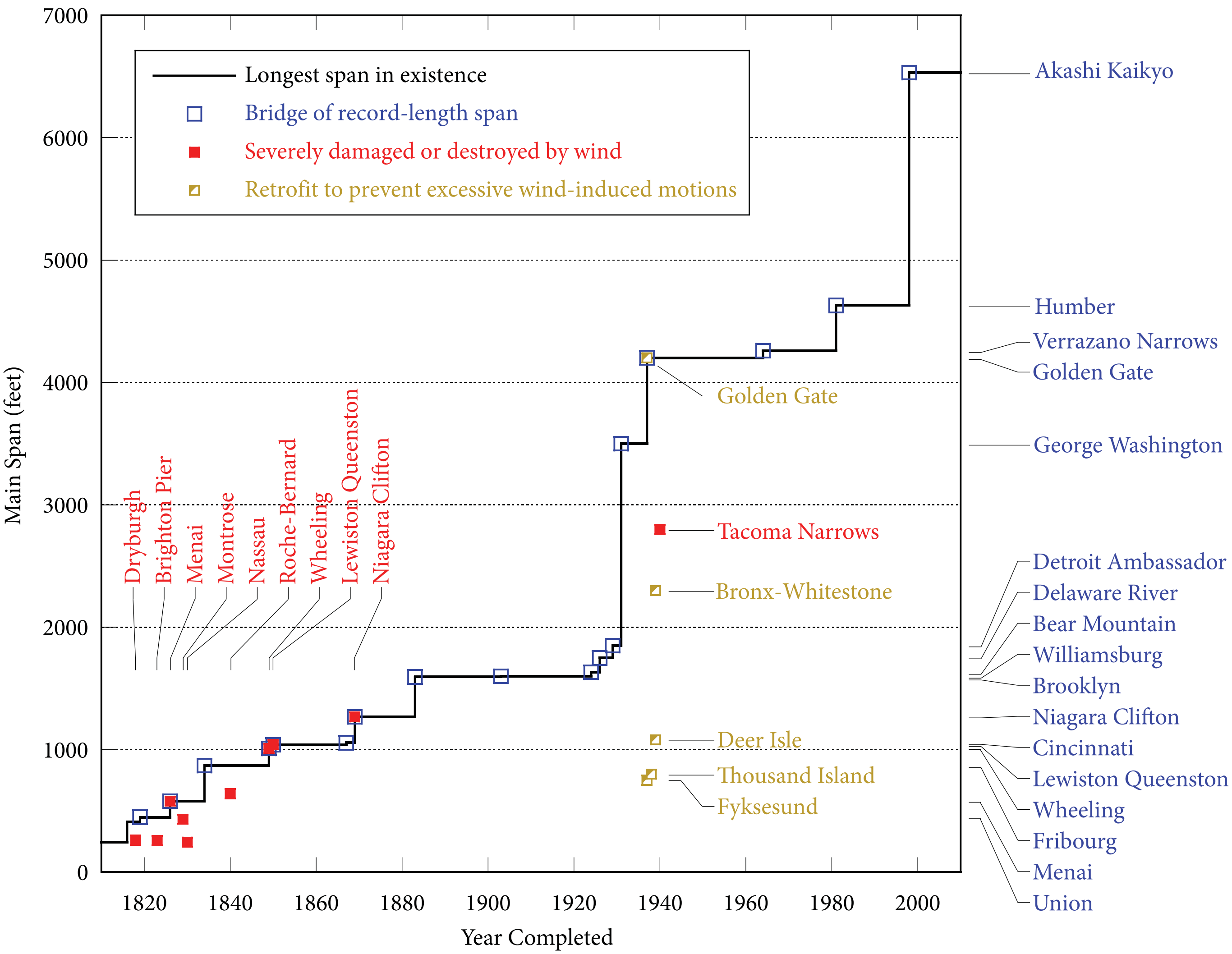
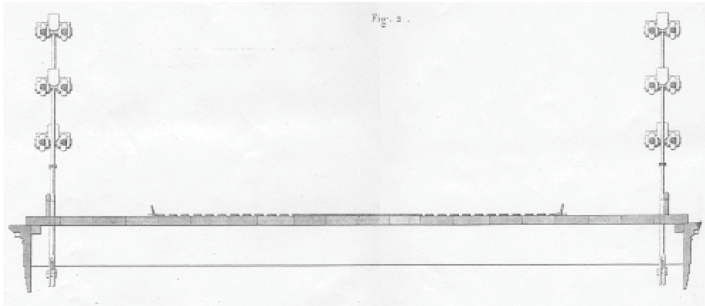


Figure 2

The Union Bridge (1820) over the River Tweed between England and Scotland is an unstiffened suspension bridge designed by Samuel Brown [left: photo by author, right: Navier (1823), Pl. III].



sion bridges. The second part discusses Roebling's development of the stayed suspension bridge form and the methods he used to design the bridges. The published design calculations for both the Niagara Railroad Bridge and Cincinnati Bridge are reviewed in detail. The third part presents the mathematical analysis of the deck-stiffened suspension bridge and discusses the influence of advanced structural analysis on the design of early 20th century suspension bridges. This part also presents a new non-dimensional formulation which aids in the understanding of the theory and practice, and also allows comparison of bridges of widely varying scales.

Early 19th Century Suspension Bridges

Design

Typical early 19th century suspension bridges were characterized by unstiffened bridge decks which provided no substantial resistance to deformation from passing live loads or wind forces. Yet such bridges could still provide serviceable passage for pedestrians, wheeled carts or animals (Figure 2). An unstiffened suspension bridge presents two fundamental structural design problems—first, to provide cables of sufficient strength to support the total load of the bridge; and second, to provide a serviceable deck surface. The cable strength directly affects the safety of the entire bridge, as failure of a main cable will result in collapse of the entire bridge. On the other hand, excessive motion or even localized failure of the bridge deck does not imply collapse of the entire structure. The decks of early unstiffened suspension bridges were often damaged and could easily be repaired or strengthened.

In order to design an unstiffened suspension bridge, early 19th century engineers sought to determine the maximum possible suspended weight that could be supported by a cable or chain of known axial strength; in other words, a relationship between bridge weight and maximum cable tension. The weight distribution of a typical suspension bridge is most closely approximated as uniformly distributed along the horizontal, in which case the cable takes the shape of a parabola (Figure 3). Initially this relationship was investigated experimentally in the United States by James Finley and in England by Thomas Telford and William Provis.

Finley demonstrated that for a given span, a smaller sag will result in higher tension and thus less supporting strength. Finley provided specific values of strength for several sag-to-span ratios, and also determined correctly that a sag-to-span ratio of about 1:6 will result in a maximum tension equal to the total suspended weight. Finley's own suspension bridge designs included chains with a relatively deep sag and a substantial trussed railing. Finley described the function of the stiffening truss as providing load distribution across multiple suspender locations. Finley does give recommended sizes for certain wooden members in the truss and deck system, although no general methods are provided for sizing members.[4]

Similar experiments on wire strength were performed in 1814 by Telford and Provis for a proposed suspension bridge at Runcorn, and the published results became widely used for design. In the 1820s the development of mathematical expressions for the tension in a parabolic cable and vertical deflection provided designers with the first structural analysis tools specific to suspension bridges. The analytically calculated cable strengths agreed well with existing experimental results and quickly obviated reliance on the experimental data.[5]

Theory of the Unstiffened Suspension Bridge

A cable hanging under its own weight, uniform along its length, takes the shape of a catenary. A cable with a vertical load uniformly distributed along the horizontal projection takes the shape of a parabola. The mathematical solution of the catenary is attributed to James Bernoulli in 1691. Interestingly, the mathematically simpler, but more practical, case of the parabolic cable was first solved by Nicholas Fuss in 1794 for a proposed suspension bridge over the Neva River in St. Petersburg.[6] This section presents the basic equations for cable tension and vertical deflection of an unstiffened suspension bridge, and discusses the structural design implications of the theoretical results.[7]

For a parabolic cable the horizontal component of cable tension, H, is given by

$$H = \frac{wL^2}{8f} = \left(\frac{W}{8}\right)\left(\frac{L}{f}\right) \qquad (1)$$

where L is the span, f is the sag, w is the weight per unit length, and W is the total weight. The maximum tension, T, occurs at the

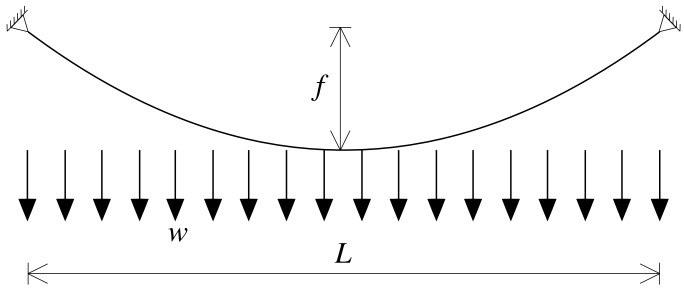


Figure 3

An unstiffened suspension bridge cable of span L and sag f subjected to uniform dead load w takes the shape of a parabola.

location of greatest cable slope, and is given by

$$T = \left(\frac{W}{8}\right)\left(\frac{L}{f}\right)\sqrt{1 + 16\left(\frac{f}{L}\right)^2} \qquad (2)$$

This equation shows that the maximum cable tension depends only on the total weight of the bridge (W) and the sag-to-span ratio, (f/L). For a given bridge span (L) and weight (W) a shallower cable will produce a greater tension and thus require a larger cable cross-sectional area. Solutions to Eq. (2) were tabulated by 19th century designers for a variety of sag-to-span ratios, and thus could be easily applied to any bridge under consideration. Such tables appear frequently in the design notebooks of John Roebling,[8] as well as published handbooks such as Trautwine's *Civil Engineer's Pocket-Book* (Figure 4).[9]

In the early 1820s Claude Navier traveled to England to study the early suspension bridges there. Navier met with suspension bridge designers Samuel Brown and Marc Brunel and reviewed plans for the Menai Bridge.[10] Upon his return to France, Navier published in 1823 the *Mémoire sur les ponts suspendus*,[11] the first treatise on suspension bridges to include substantial mathematical analysis, and his results would have a major influence on the development of suspension bridge design (Figure 5). Navier derived the earliest-known expression for the vertical deflections, v, of an unstiffened suspension bridge due to a concentrated live load, P, placed at mid-span, including the effect of the initial self-weight of the bridge, W (Figure 6). The vertical deflection is given by

Figure 5

Table of suspension bridge design values, including ratio of maximum cable tension to bridge weight (fourth column) based on the sag-to-span ratio (first column) [Trautwine 1908].

Figure 4

Mémoire sur les ponts suspendus (1823) by Claude L.M.H. Navier is the first major theoretical work on suspension bridge behavior.

Figure 6

Navier's equation (3, 12) quantifies the vertical deflection due to a point load at mid-span of an unstiffened suspension cable in terms of other bridge properties.

SUSPENSION BRIDGES.

Art. 1. Table of data required for calculating the main chains or cables of suspension bridges. Original.

Deflection in parts of the Chord.	Deflection in Decimals of the Chord.	Length of Main Chains between Suspension Piers, in parts of the Chord.	Tension on all the Main Chains at either Suspension Pier, in parts of the entire Suspended Wt. of the Bridge, and its Load.	Tension at the Center of all the Main Chains; in parts of the entire Suspended Wt. of the Bridge, and its Load.	Angle of Direction of the Chains at the Piers. Deg.	Min.	Natural Sine of the Angle of Direction of the Chains, at the Piers.	Natural Cosine of the Angle of Direction of the Chains at the Piers.
1-40	.025	1.002	5.03	5.00	5	43	.0995	.9950
1-35	.0286	1.002	4.40	4.37	6	31	.1135	.9935
1-30	.0333	1.003	3.78	3.75	7	36	.1322	.9912
1-25	.04	1.004	3.16	3.12	9	6	.1580	.9874
1-20	.05	1.006	2.55	2.51	11	19	.1961	.9806
1-19	.0526	1.007	2.43	2.38	11	53	.2060	.9786
1-18	.0555	1.008	2.30	2.25	12	32	.2169	.9762
1-17	.0588	1.009	2.18	2.12	13	14	.2290	.9734
1-16	.0625	1.010	2.06	2.00	14	2	.2425	.9701
1-15	.0667	1.012	1.94	1.87	14	55	.2573	.9663
1-14	.0714	1.013	1.82	1.74	15	57	.2747	.9615
1-13	.0769	1.016	1.70	1.62	17	6	.2941	.9558
1-12	.0833	1.018	1.57	1.49	18	33	.3180	.9480
1-11	.0919	1.022	1.46	1.37	19	59	.3418	.9398
1-10	.1	1.026	1.35	1.25	21	48	.3714	.9285
1-9	.1111	1.033	1.23	1.12	23	58	.4062	.9138
⅛	.125	1.041	1.12	1.00	26	33	.4471	.8945
1-7	.1429	1.053	1.01	.881	29	45	.4961	.8726
3-20	.15	1.058	.972	.833	30	58	.5145	.8574
⅙	.1667	1.070	.901	.750	33	41	.5547	.8320
1-5	.2	1.098	.800	.625	38	40	.6247	.7808
	.225	1.122	.747	.555	42	0	.6690	.7433
¼	.25	1.149	.707	.500	45	00	.7071	.7071
.3	.3	1.206	.651	.417	50	12	.7682	.6401
⅓	.3333	1.247	.625	.375	53	8	.8000	.6000
.4	.4	1.332	.589	.312	58	2	.8483	.5294
9-20	.45	1.403	.572	.278	60	57	.8742	.4855
½	.5	1.480	.559	.250	63	26	.8944	.4472

These calculations are based on the assumption that the curve formed by the main chains is a parabola; which is not strictly correct. In a finished bridge, the curve is between a parabola and a catenary; and is not susceptible of a rigorous determination. **It may save some trouble in making the drawings** of a suspension bridge, to remember that when the deflection does not exceed about $\frac{1}{10}$ of the span, a segment of a circle may be used instead of the true curve; inasmuch as the two then coincide very closely; and the more so as the deflection becomes less than $\frac{1}{10}$. The dimensions taken from the drawing of a segment will answer all the purposes of estimating the quantities of materials.

The deflection usually adopted by engineers for great spans is about $\frac{1}{12}$ to $\frac{1}{15}$ the span. As much as $\frac{1}{10}$ is generally confined to small spans. The bridge will be stronger, or will require less area of cable, if the deflection is greater; but it then undulates more readily; and as undulations tend to destroy the bridge by loosening the joints, and by increasing the momentum, they must be specially guarded against as much as possible. The usual mode of doing this is by trussing the hand-railing; which with this view may be made higher, and of stouter timbers than would otherwise be necessary. In large spans, indeed, it may be supplanted by regular bridge-trusses, sufficiently high to be braced together overhead, as in the Niagara Railroad bridge, where the trusses are 18 ft high; supporting a single-track railroad on top; and a common roadway of 19 ft clear width, below.*

* The writer believes himself to have been the first person to suggest the addition of very deep trusses braced together transversely, for large suspension bridges. Early in 1851, he designed such a bridge, with four spans of 1000 ft each; and two of 500; with wire cables; and trusses 20 ft high. It was intended for crossing the Delaware at Market Street, Philada. It was publicly exhibited for several months at the Franklin Institute, and at the Merchants' Exchange; and was finally stolen from the hall of the latter. Mr Roebling's Niagara bridge, of 800 ft span, with trusses 18 ft high, was not commenced until the latter part of 1852; or about 18 months after mine had been publicly exhibited.

RAPPORT

A Monsieur BECQUEY,

CONSEILLER D'ÉTAT,

DIRECTEUR GÉNÉRAL DES PONTS ET CHAUSSÉES ET DES MINES;

ET

MÉMOIRE

SUR LES PONTS SUSPENDUS;

Par M. NAVIER,

INGÉNIEUR EN CHEF AU CORPS ROYAL DES PONTS ET CHAUSSÉES.

A PARIS,

DE L'IMPRIMERIE ROYALE.

1823.

123. En divisant l'équation précédente par l'équation (23), article 115, il vient

$$\frac{f'^2}{f^2} = \frac{1 + \frac{\Pi}{2ph} + \frac{9}{10}\left(\frac{c-h}{h}\right) - \frac{54}{175}\left(1 - \frac{\Pi}{2ph}\right)\left(\frac{c-h}{h}\right)^2 + \&c.}{1 + \frac{9}{10}\left(\frac{c-h}{h}\right) - \frac{54}{175}\left(\frac{c-h}{h}\right)^2 + \&c.}$$

La valeur du second membre diffère très-peu de $1 + \frac{\Pi}{2ph}$ (*) : nous avons donc, à fort peu près,

$$f' = f\sqrt{1 + \frac{\Pi}{2ph}};$$

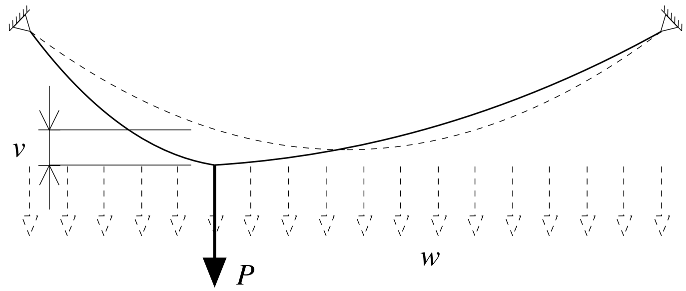
d'où l'on tire, en développant le radical, et négligeant toujours les puissances supérieures de la fraction $\frac{\Pi}{2ph}$,

$$f' - f = \frac{\Pi f}{4ph}. \qquad (12)$$

On voit d'après cela que, toutes les fois qu'un poids placé au milieu de la longueur du plancher est petit par rapport au poids total du pont, la valeur absolue de l'abaissement produit par ce poids est représentée à très-peu près par la fonction $\frac{\Pi f}{4ph}$. Ainsi cet abaissement est, pour un poids donné, proportionnel à la flèche de la courbe décrite par les chaînes, et réciproque au poids total du pont : il est le même pour divers ponts dans lesquels les flèches seraient proportionnelles aux ouvertures.

Figure 7

An unstiffened suspension bridge cable subjected to dead load w and live load P takes the form of two parabolic segments and deflects a vertical distance v from the dead load configuration.



$$v = \left(\frac{f}{2}\right)\left(\frac{P}{W}\right) \tag{3}$$

The application of the live load also produces an increase in the horizontal component of cable tension, h, given by

$$h = \left(\frac{3}{16}\right)\left(\frac{L}{f}\right)P \tag{4}$$

Later authors would extend Navier's results for a concentrated load positioned anywhere on the span.[12]

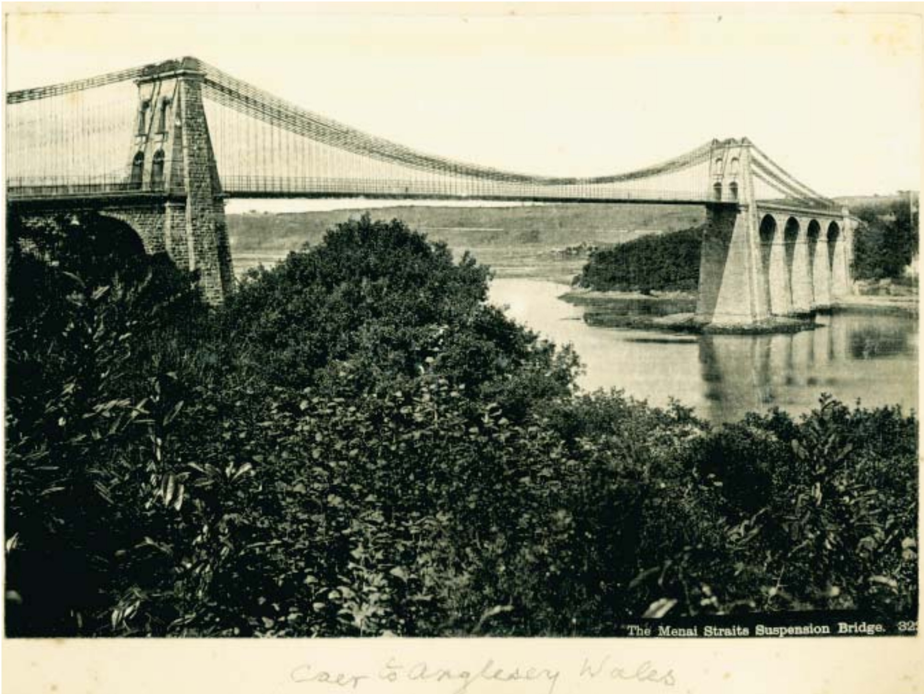
Unstiffened suspension bridges exhibit large deflections under the application of non-uniform live loads. In order to support the concentrated live load, the cable must change to the funicular shape for the combined dead (uniform) and live (concentrated) load (Figure 7). The application of the concentrated live load changes the cable shape from a single parabola to two parabolic cable segments with discontinuous slope at the point of load application. Navier's equation for vertical deflection provides a mathematical expression for the concept of cable stiffness—the ability of a suspension cable to resist deformation due to an existing tension force. In this case, the self-weight of the bridge (W) produces the initial tension, and the vertical deflection due to live load is inversely proportional to the weight. A geometrically non-linear solution, which enforces equilibrium on the deformed shape of the cable, is necessary in order to capture the effect of self-weight in creating cable stiffness.

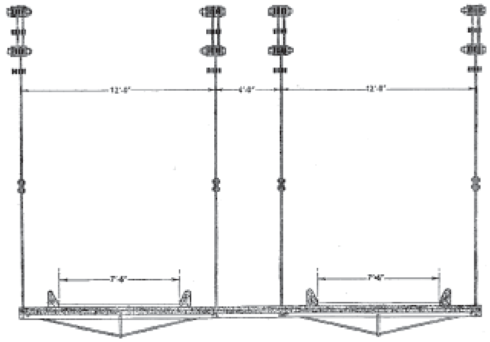
Limiting live load deflections was a primary design concern for unstiffened suspension bridges. Navier's equation relating deflections to basic bridge properties provided designers with a mathematical tool on which to base their designs. For a given span length and live load, a shallower cable sag and larger bridge weight will reduce vertical deflections. Increasing the weight of the bridge and decreasing the cable sag both increase the live load cable tension, the horizontal component of which is given by h from Eq. (4). The live load tension is typically much smaller than the dead load tension, and therefore the associated increase in total cable tension due to a shallower cable profile would be small and could easily be accommodated with a larger cable cross-sectional area. Navier's own suspension bridge designs for a canal aqueduct and road bridge reflected his theoretical findings with shallow cable profiles and heavy, unstiffened decks.[13] The design for the road bridge had a sag-to-span ratio of only 1:15, as compared to ratios of approximately 1:10 typical of the earlier unstiffened bridges in England.[14] The design of the road bridge became the basis for the Pont d'Invalides in Paris for which construction began in 1824, but the bridge was never completed after partial failure of an anchorage in 1826.[15]

Navier's theoretical analysis of the unstiffened suspension bridge would be reflected in suspension bridge design practice in both Europe and America. Although Telford's design of the Menai Straits Bridge (Figure 8) as an unstiffened form was completed prior to the publication of Navier's treatise, Navier's concepts influenced the repairs to the bridge. After the bridge was severely damaged by wind in January 1839, the deck was reconstructed and strengthened, adding 130 tons to the original deck weight of 623 tons. A longitudinal stiffening truss would not be added until the 1940 reconstruction.[16] In the United States, Trautwine's *Pocket-Book* discussed qualitatively the relationship between sag, required cable area and vertical deflections consistent with Navier's equations (Figure 4).[17] Even John Roebling used Eq. (3) to calculate vertical deflections of the Niagara Railroad Bridge, and he compared those values to measured deflections (Figure 10). Significantly, Roebling did not use Navier's equation to drive

Figure 8

Thomas Telford's Menai Straits Bridge and a cross-section of the original unstiffened deck [left: author's collection, right: Maunsell 1946].





the design of his bridge, but only as one of several independent means to evaluate its performance.

Navier's influence is perhaps best demonstrated through the work of the American bridge designer, Charles Ellet, who had studied at the École Nationale des Ponts et Chaussées in Paris during the 1830s.[18] Ellet designed the Wheeling Bridge (1849) with a main span of 1010 feet, the first bridge span to exceed 1000 feet and the longest span in the world at the time (Figure 9). Ellet used a very shallow cable profile, with a sag-to-span ratio of 1:17, and included a heavy deck with only a very light trussed railing. Ellet criticized the concept of truss-stiffening, stating

> … charletan proposals to stiffen such bridges by trusses, so as to give them an artificial rigidity which they do not derive from their principles of equilibrium.[19]

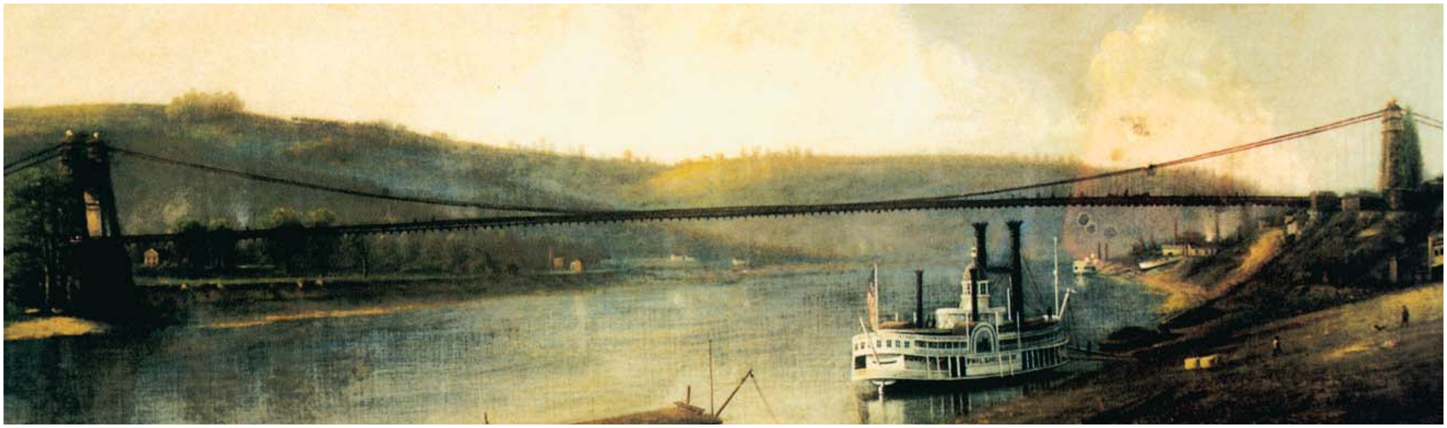
And Ellet was a strong proponent of cable stiffness through weight

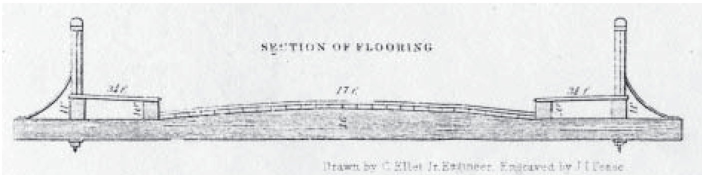
> Although as an auxiliary, and within moderate limits, trusses may be advantageously applied, permanent strength and stiffness can be most cheaply obtained in suspension bridges of very great span, by the addition of weight.[20]

The Wheeling Bridge was destroyed in wind storm on May 17, 1854 exhibiting large vertical and torsional motions.

Figure 9

Charles Ellet's Wheeling Suspension Bridge (1849) and a cross-section of the unstiffened deck [top: Kemp and Fluty 1999, bottom: Ellet 1851].





Design for Wind Resistance

Previous historical research has clearly established that early 19th century unstiffened suspension bridges exhibited excessive wind-induced motion (Figure 1).[21] Multiple bridges were severely damaged or destroyed in wind storms and preventing such failures became a primary design challenge which was discussed in contemporary engineering journals and treatises. Navier recognized that the complex nature of wind forces on bridges was beyond existing theoretical capabilities

> Les accidens qui resulteraient de cette action ne peuvent etre apprecies et prevenus que d'apres des lumieres fournies par l'observation et l'experience.[22]
>
> [The accidents that would result from this action can be appreciated and prevented only from knowledge provided by observation and experience.]

Nineteenth century designers proposed and employed a variety of methods to stiffen suspension bridges against excessive motion, including trusses, stays and reverse cables. In France the Seguin brothers used a stiffening truss in the Saint Vallier and Tain-Tournon Bridges, and their writings clearly indicate that it was intended to reduce motions of the bridges.[23] In England the Montrose Bridge was heavily damaged in 1838, and James Rendel reconstructed the bridge with eight foot deep timber stiffening trusses.[24] Drawings for the second Dryburgh Abbey Bridge of 1818 published in Navier's *Mémoire* show inclined stays, although it is not known if they were ever constructed.[25] The description and drawings of Samuel Brown's Trinity Pier, also published in Navier's *Mémoire* include inclined stays, but they were never built.[26] A unique stiffening method of reversed suspension chains was used by Marc Brunel for his two Bourbon Bridges of 1823.[27] This same stiffening method would be proposed anew more than

Figure 10

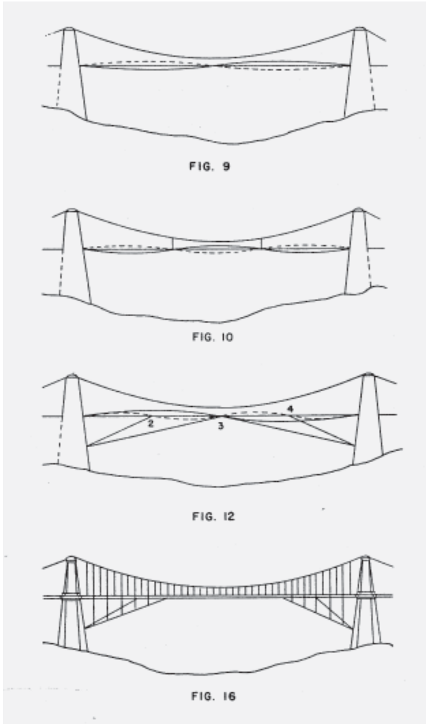
John Roebling's calculation of the deflection of the Niagara Railroad Bridge using Navier's equation [Roebling 1855].

Let x represent the deflection of cables in feet.
w " the weight in the center in tons,
and W " the weight of the whole structure,
then the formula $\frac{x\ w}{2\,W}$ will give the depression, produced in the center, in feet. Substituting now 59 feet for x, 47 for w, and 1000 for W, we shall have

$$\frac{59\times47}{2\times1000} = 1.386 \text{ feet.}$$

Figure 11

Diagrams by John Scott Russell describing the application of underfloor stays to prevent vertical oscillations in a discussion of the 1837 failure of the Brighton Chain Pier [Russell 1839].



150 years later by two applied mathematicians.[28] In a discussion of the 1836 failure of the Brighton Chain Pier, John Scott Russell proposed stays specifically as a means of protecting suspension bridges against wind-induced motions (Figure 11).[29] In the late 19th century, French designer Ferdinand Arnodin continued the tradition of the stayed-suspension bridge, although he did not connect the deck and suspension cable with vertical suspenders in the area of the stays.[30] This type of design had in fact been discussed by Roebling in the context of the Cincinnati Bridge; however Roebling preferred to retain the vertical suspenders to provide redundancy.[31] In 2008 inclined stays in combination with a parabolic cable were used again on the North Avenue Bridge in Chicago to allow for a shallower stiffened deck and maintain sufficient river clearance.[32]

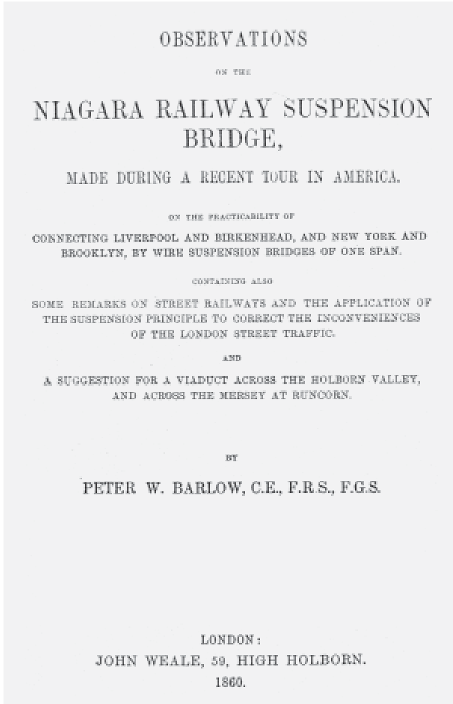
The Work of John A. Roebling

The career of John Roebling can be interpreted in terms of the three I's—*imitation, innovation, inspiration*—first proposed by David Billington as one characteristic of structural artists. Roebling was highly proficient in the current aspects of suspension bridge design and theory, and thus was capable of designing suspension bridges in *imitation* of the exiting state-of-the-art. His mastery of existing theory and application of it to his own bridges is evident in his early design calculations and technical writings.[33] For example, Roebling used Eq. (2) to calculate the maximum cable tension and Eq. (3) to estimate vertical deflections (Figure 10). In addition, Roebling made careful observations and measurements of the performance of his own bridges as well as those of other designers.

But Roebling would ultimately go beyond simple imitation of existing practice in the design of his suspension bridges. In order to build spans of record breaking length, capable of carrying heavy rail traffic, and without excess vertical motion, Roebling developed a bridge system which combined suspension cables, inclined stays and stiffening trusses. Although inclined stays became the visual trademark of a Roebling bridge, other designers before Roebling had proposed and built both stayed and truss-stiffened suspension bridges. Roebling's true *innovation* was his develop-

Figure 12

Peter Barlow's 1860 report on his visit to inspect Roebling's Niagara Railroad Bridge.



OBSERVATIONS

ON THE

NIAGARA RAILWAY SUSPENSION BRIDGE,

MADE DURING A RECENT TOUR IN AMERICA.

ON THE PRACTICABILITY OF

CONNECTING LIVERPOOL AND BIRKENHEAD, AND NEW YORK AND BROOKLYN, BY WIRE SUSPENSION BRIDGES OF ONE SPAN.

CONTAINING ALSO

SOME REMARKS ON STREET RAILWAYS AND THE APPLICATION OF THE SUSPENSION PRINCIPLE TO CORRECT THE INCONVENIENCES OF THE LONDON STREET TRAFFIC.

AND

A SUGGESTION FOR A VIADUCT ACROSS THE HOLBORN VALLEY, AND ACROSS THE MERSEY AT RUNCORN.

BY

PETER W. BARLOW, C.E., F.R.S., F.G.S.

LONDON:
JOHN WEALE, 59, HIGH HOLBORN.
1860.

ment of a rational design approach for the stayed, truss-stiffened suspension bridge based on principles of strength, redundancy and ductility. Roebling's design approach allowed him to design safe and serviceable suspension bridges without being constrained by Navier's straightjacket.

The work of Roebling served as an *inspiration* to other bridge engineers and designers. Roebling's Niagara Railroad Bridge became an engineering sensation, the direct impetus for the development of the first theory of the stiffened suspension bridge, and an international cultural landmark. Deck or truss stiffened suspension bridges had arisen in practice in the mid-19th century as an effective manner of limiting vertical deflections of suspension bridges due to both non-uniform live loads and wind loads, prior to the existence of any analysis method for determining forces in the truss and sizing its members. The effect of the lack of an accurate analysis method on structural form is illustrated by the design process of Robert Stephenson's Britannia Bridge of 1850. Stephenson originally considered using suspension chains to support the massive tubular girders. But at the conclusion of Stephenson's design process, which included substantial new research and experimentation on the behavior of thin-walled tubular girders, the girders were determined to be strong and stiff enough to support their own weight as well as the rail traffic without the need for the suspension chains. In the meantime the towers had already been completed to accommodate the suspension chains and remained in place as a visual reminder of Stephenson's design process.[34] Based on his experience, Stephenson concluded that suspension bridges could not be made stiff enough to carry rail traffic, and Stephenson is believed to have written to Roebling regarding his Niagara Railroad Bridge "If your bridge succeeds, then mine have been magnificent blunders." [35] Roebling himself compared the performance and economy of his Niagara Bridge to Stephenson's tubular Conway Bridge.[36] The scientific, social and symbolic comparison between Roebling's Niagara Railroad Bridge and Stephenson's Britannia Bridge has become a classic illustrative example of structural art.[37]

British engineer Peter Barlow visited the Niagara Railroad Bridge, conducted field measurements, and then performed a series of scale-model experiments of railway suspension bridges (Figure 12). Barlow concluded that a deck-stiffened suspension bridge could have as little as 1/25th of the structural material as would be required for an unsuspended girder bridge.[38] Shortly thereafter William J.M. Rankine published the first theory of the deck-stiffened suspension bridge in order to provide a mathematical explanation for Barlow's experimental results stating

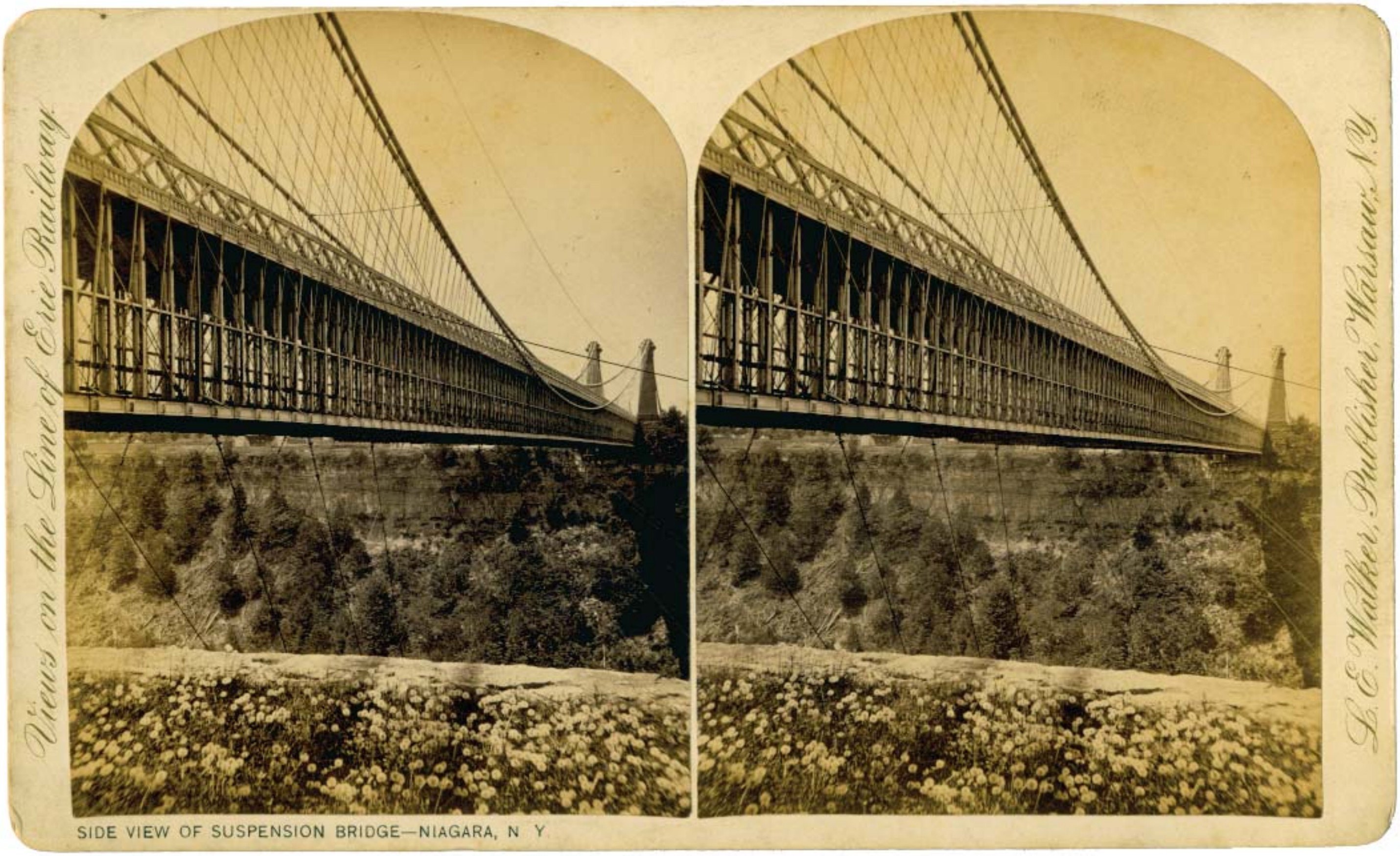
> If mathematicians had directed their atention to the subject, they might have anticipated this result.[39]

Figure 13

Roebling's Niagara Railroad Bridge was a frequent subject of 19th century stereophotographs [Author's collection].

The success of Roebling's Niagara Railroad Bridge led to the physical experiments by Barlow and then to the first theoretical analysis of the deck-stiffened suspension bridge by Rankine. The existence of a theoretical formulation for the behavior of a deck-stiffened suspension bridge would ultimately contribute to the disappearance of the use of inclined stays as a load carrying and stiffening element. Thus one of the most practical, efficient and successful means of limiting dynamic motions in suspension bridges would be discouraged because it was not theoretically tractable.

Not just an engineering sensation, Roebling's Niagara Railroad Bridge became a worldwide cultural landmark as well. Roebling's bridge was built in the right place—at one of the world's most popular 19th century tourist destinations; and at the right time—during the boom years of stereo-photography. The Niagara Falls area is believed to have been one of the most photographed areas of the world in the second half of the 19th century, and viewing of stereo-photographs was one of the earliest forms of mass-market entertainment, predating radio and television.[40] Roebling's Niagara Railroad Bridge is the subject of numerous stereograms (Figure 13). Mark Twain memorialized the experience of crossing the bridge with his uniquely American wit

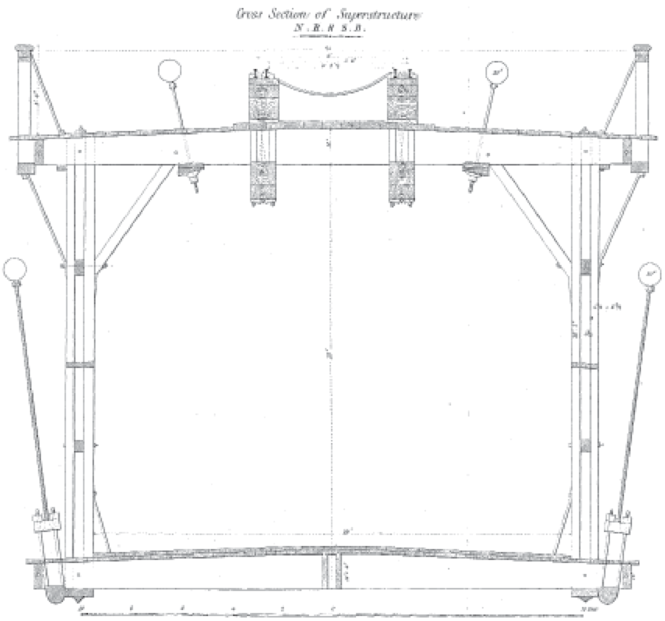


Then you drive over to Suspension Bridge, and divide your misery between the chances of smashing down two hundred feet into the river below, and the chances of having the railway train overhead smashing down on to you. Either possibility is discomforting taken by itself, but, mixed together, they amount in the aggregate to positive unhappiness.[41]

Passage across the Niagara Railroad Bridge became the final leg on the long road to freedom for many escaped slaves during the American Civil War. The biography of abolitionist Harriet Tubman describes slaves emerging from hiding as wagons crested the crown at the center of the bridge, the dividing line between America and Canada.[42] For these escaped slaves, the sight and

Figure 14

Cross-section of the Niagara Railroad Bridge showing the box truss with railway on the upper level and carriageway below [Roebling 1855].



sound of freedom was the deep gorge below and the roar of falls, experienced from Roebling's bridge.

Roebling's Niagara Railroad Bridge is arguably the first signature bridge—both an engineering masterpiece and a cultural icon. Importantly Roebling's bridge achieved this status not by chance, but by intention. Roebling's bridge integrates the scientific, social and symbolic ideals of structural art to the utmost degree, a feat he would repeat in his design for the Brooklyn Bridge. After the Niagara Bridge opened, some engineers criticized the slow speed limit of five miles per hour for trains crossing the bridge and suggested it was evidence of the bridge's lack of strength and safety. In his 1860 *Report*, Roebling addressed this scientific question with a social and symbolic answer

> Passengers will prefer to cross at a slow rate in order to enjoy the splendid scenery during the passage.[43]

Innovation: The Concept and Evolution of Roebling's System

The success of Roebling's designs relied on his application of the structural design principles of strength, redundancy and ductility to the behavior of his relatively complicated structural system at failure, rather than on the ability to mathematically analyze the internal forces in the highly indeterminate and non-linear structure. The origin of Roebling's strength-based design approach is evident in his published writings about his first suspension bridge, the Pittsburgh Aqueduct (1845). This seven span aqueduct used suspension cables and a stiffened wooden trunk to carry loads. As there is essentially no unbalanced loading in an aqueduct, stays are not necessary. Of his design concept, Roebling wrote

> The original idea upon which the plan has been perfected, was to form a wooden trunk, strong enough to bear its own weight, and stiff enough for an aqueduct or bridge, and to combine this structure with wire cables of a sufficient strength to bear safely the great weight of water.[44]

The "true" distribution of forces between the suspension cables and stiffened trunk would depend on the sequence of construction and load application, and almost certainly would not correspond to Roebling's conceptual model. However, as long as the bridge has redundancy and the ability to share load (ductility), Roebling's design approach is entirely rational.[45]

Roebling's first two applications of inclined stays were at the Smithfield St. Bridge (1846) and the Allegheny Bridge (1860), both multi-span roadway bridges. In these bridges the stays were conceived of as a method of equalizing the effect on unbalanced live loads on adjacent spans. As Roebling's understanding of the stayed suspension bridge evolved, the stays became a primary stiffening element, in concert with the deck truss and cable stiffening. In the *Final Report* for the Niagara Railway Bridge, Roebling wrote

> The means employed are; *Weight, Girders, Trusses* and *Stays*. With these any degree of stiffness can be insured, to resist either the action of trains, or the violence of storms, or even hurricanes; … And I will here observe, that no Suspension Bridge is safe without some of these appliances. [italics original][46]

> But their [the stays] principle service is to preserve the equilibrium of the structure under heavy loads, and to assist the trusses and girders.[47]

Roebling's use of the term "girders" refers to the heavy timber beams directly supporting the rails themselves; whereas "trusses" refers to the box truss formed by the superstructure of the bridge (Figure 14). Finally, in the designs for the Cincinnati Bridge (Figure 15) and Brooklyn Bridge, Roebling would use the system of inclined stays not just as a stiffening element but also as a primary load carrying system. This concept is echoed in Roebling's well-known statement about the Brooklyn Bridge

> The latter [the floor] in connection with the stays will support itself without the assistance of the cables ... If the cables were removed, the Bridge would sink in the centre, but would not fall.[48]

Design Methods of John A. Roebling

Examination of Roebling's writings and design calculations reveals his conception of the structural behavior of his suspension bridges and its evolution over time. Roebling needed to estimate design forces in the suspension cables, inclined stays and stiffening truss without the ability to perform indeterminate structural analysis. However for a strength-based design approach, the assumed division of total load need not be constrained by compatibility of deformations. As long as ductility and redundancy are provided, the total strength must only satisfy equilibrium and include some reasonable factor of safety. Elements of the structure that are not considered part of the primary load carrying system can be sized based on serviceability considerations.

Roebling's design approach has been previously studied based on preliminary design calculations from the years 1847 to 1873 for fifty-nine unbuilt suspension bridge designs with spans in the range of 100 ft to 600 ft completed by both John and Washington Roebling.[49] These design calculations are typically only a few pages in length but capture the fundamental design decisions necessary for initial design. In nearly all of these designs, 2/3 to 3/4 of the total load was assigned to the suspension cables, and the remaining 1/4 to 1/3 was assigned to the stays. None of the vertical load was assigned to the stiffening truss, as its intended function was to help distribute loads along the length of the bridge. These design calculations also show that Roebling varied the cross-sectional area of the stays, since their axial tension forces would vary with angle of inclination.

The following sections explore in more detail Roebling's published design calculations for the Niagara Railroad Bridge and the Cincinnati Bridge.[50] Roebling's calculations address several fundamental structural design issues, such as estimation of live loads, design loads for each sub-system, sizing of the cables and stays, and design for wind loads. Roebling's calculations demonstrate several modern concepts of structural design, including a strength-based approach, consideration of both extreme and common live loads, and use of different safety factors for different components of the bridge. Notably no technical design information on sizing of the stiffening truss is included in his published calculations, reflecting the idea that the strength of the stiffening truss is not critical to the overall strength of the bridge.

Figure 15

Roebling’s Cincinnati Bridge (1867), original appearance prior to the 1896 reconstruction [Author's collection].

THE OHIO SUSPENSION BRIDGE AT CINCINNATI.

Niagara Railroad Bridge

Suspension Cables

Roebling estimated the suspended dead weight of the bridge to be 1000 tons, including the downward pull from wind guys anchored into the gorge below. Roebling considered a rarely occurring live load due to a train of 200 tons on the upper deck and 50 tons from carriages and pedestrians on the lower deck. Both of these loads were assumed to be uniformly distributed along the length of the bridge. Given the sag-to-span ratio of 1:14, the ratio of maximum cable tension (*T*) to weight (*W*) from Eq. (2) is 1.81. Thus the maximum cable tension from the dead load was 1810 tons; and from the live load, 452 tons. The four main suspension cables had a combined strength of 12,000 tons, based on a total of 14,560 No. 9 wires, each with a specified breaking strength of 90,000 psi. In sizing the suspension cables, Roebling assumed all of the dead and live loads were carried by the suspension cables. The safety factor for the dead load cable tension was about 6.6; and for combined dead and live load, about 5.3.

Inclined Stays

Although Roebling viewed the stays primarily as a stiffening element, he did estimate that the stays relieved the main cables of about 153 tons of vertical load under typical live load conditions. Roebling does not explicitly derive the value of 153 tons in published documentation, but this value can be approximately confirmed based on values used elsewhere in the *Final Report*. In discussing the horizontal stability of the saddles, Roebling cited a working axial force of 4 tons per stay with a corresponding horizontal component of 3.5 tons. These tension forces can be used to determine a representative stay angle of 29 degrees above the horizontal; whereas the inclination of the actual stays varied from about 20 degrees to 60 degrees.[51] In discussing the design of the stays themselves, Roebling cited an axial tension of 5 tons per stay from the dead load only. Based on the stay angle of 29 degrees, the resulting total vertical force from all 64 stays would be about 155 tons, which is close to the value of 153 tons given by Roebling. Thus of the 1000 tons dead load, the stays could support approximately 15%.

Each stay consisted of 1-3/8 inch diameter wire rope with an ultimate strength of 30 tons. This ultimate strength is assumed to represent the pure axial strength, and is consistent with the tables of design strengths published by the Roebling wire works in Trenton, New Jersey. For an axial tension of 5 tons from dead load, the safety factor was 6. Roebling conservatively assumed that the extreme live load of 250 tons was carried entirely by the stays, with a resulting typical axial tension of 1.25 tons per stay. Thus the safety factor for the stays under combined dead and live load was about 4.8. The relatively large factor of safety allowed for variability of the stay tension due to actual inclination angle as well as the effects of concentrated live loads. The *Final Report* does not contain any specific calculations which address the effects of non-uniform live loads on the stay forces, but Roebling does consider the local effects of live loads in the design of the vertical suspenders.

Vertical Suspenders

The vertical suspenders are necessary to transfer loads from the bridge deck to the suspension cables. Although the suspenders appear to be relatively straightforward pure tension members, they must be sized based on the effects of concentrated live loads and their spacing will affect the design of the stiffening truss. Failure of one or more suspenders in a suspension bridge could potentially lead to progressive failure of the stiffening truss. Since live load moments in the truss are proportional to the square of the unsupported length, failure of a single suspender would increase the truss moments fourfold.

Roebling divided the dead weight of 1000 tons equally between 624 suspenders giving 1.6 tons per suspender. The suspenders are spaced at 5 feet. For live load, Roebling considered a locomotive and tender of 34 tons over a length of 200 feet. He estimated that most of the weight of the locomotive was concentrated over a length of only 50 feet and supported by 20 suspenders. Thus the maximum live load tension in a suspender was 1.7 tons, giving a total of 3.3 tons per suspender. The strength of each suspender was 30 tons, giving a safety factor of about 9. Thus Roebling designed the suspenders with a substantially larger safety factor than the cables or stays.

Stiffening Truss

Curiously, Roebling included no explicit calculations related to the strength or stiffness of the box truss, although his qualitative descriptions of the truss make it clear that he viewed it as integral to the successful performance of the bridge. The methodology used by Roebling and other 19th century designers to size members of the stiffening truss remains undocumented. In an unstiffened suspension bridge, the stiffening truss need only span between adjacent suspenders. In a truss-stiffened suspension bridge, the truss is intended to distribute the effects of concentrated loads along the length of the bridge and therefore would need to have sufficient stiffness and strength to span across multiple suspension points. Based on descriptions from the 1877 to 1879 renewal of the Niagara Railroad Bridge, each truss chord was constructed from multiple layers of timber in 5 foot lengths but with staggered splices to provide continuity across the suspender points.[52] The rail girders were constructed with multiple timber layers using scarfed and keyed splices to provide continuity with vertical bolts passing through the all layers to provide unity of action.

Although Roebling did not include any calculations related to the truss, he included measured data to demonstrate the effectiveness of the trusses and girders in providing overall stiffness to the bridge. Roebling cited a measured deflection of about 0.45 feet caused by a train weighing 47 tons. He compared this value to a calculated deflection of 1.386 feet from Eq. (3), assuming very conservatively that the entire live load was concentrated at midspan (see Figure 9). Roebling attributed the difference between these two deflections to the stiffening provided by the girders, trusses and stays.

Design for Wind Loads

While the Niagara Bridge was under construction, Ellet's Wheeling Bridge was destroyed in a wind storm. Roebling's technical notebooks and *Final Report* include discussion of the Wheeling failure. As an extra measure of protection Roebling added the 56 underfloor guys anchored into rock on the cliffs below the bridge.

Roebling estimated the total vertical strength of the guys as 1000 tons in resisting uplift. In addition Roebling included 600 tons from the self-weight of the superstructure, 100 tons from the self-weight of the cables and 300 tons from the uplift capacity of the truss end supports. Thus the total uplift resistance was estimated as 2000 tons. The design wind pressure of 50 psf acting across the entire surface of both the upper and lower decks creates an uplift force of 950 tons. Therefore the safety factor against uniform wind uplift was about 2. The inclined stays and stiffening truss contribute by ensuring that the bridge acts as a whole in resisting the wind, preventing any anti-symmetric sinusoidal or torsional deformations of the bridge deck.

In contrast, Roebling noted that the Wheeling Bridge had a horizontal surface area of about 25,000 square feet, which when exposed to a uniform pressure of 50 psf, resulted in an uplift force of 625 tons. The weight of the Wheeling Bridge was estimated to be only 440 tons. Further the Wheeling Bridge had no substantial stiffening truss, only a light trussed railing, therefore wind-induced forces could produce the sinusoidal and torsional motions of the bridge deck which ultimately led to its destruction.

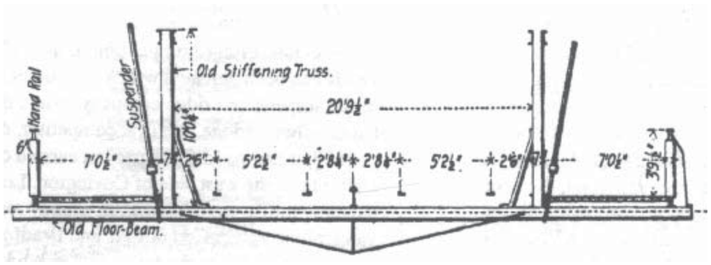
Cincinnati Bridge

Suspension Cables

Roebling estimated the total weight of the suspended span as 1500 tons, but he assumed that the weight of 100 feet of the main span nearest to each tower would be carried by the truss directly to the towers, resulting in a suspended dead weight of only 1300 tons.

Figure 16

Cross-section of the Cincinnati Bridge [Gastright 2000].



For the sag-to-span ratio of 1:11.87, the ratio of maximum cable tension to suspended weight is 1.565 (Eq. 2), and the maximum cable tension due to dead load is 2034 tons.

Roebling considered an extreme live load case of the bridge deck and sidewalks being crowded with people, creating a load of 30 psf or 360 tons. The typical live load was based on the bridge being occupied by a mix of horse drawn carriages and people, resulting in a load of 111 tons. The extreme live load caused an additional cable tension of 564 tons; and the typical live load, 174 tons. The two main suspension cables were constructed from 10,400 No. 9 wires providing an overall strength of 8424 tons. For dead load alone, the safety factor was about 4.1. For dead load plus extreme live load, the safety factor was 3.2; and for dead load plus typical live load, 3.8. Although the magnitudes of these safety factors are not unusual for 19th century structural design, they are significantly lower than those from the Niagara Bridge, which were in the range of 5 to 6.[53] Roebling did not publish these safety factors, corresponding to all of the load supported by the cables alone, rather he included the supporting strength of the stays before calculating the safety factors.

Inclined Stays

In contrast to the Niagara Bridge, Roebling explicitly calculated load sharing between the cables and inclined stays for the Cincinnati Bridge.[54] Each of the 76 stays was 2.25 inch diameter wire rope with an axial strength of 90 tons, giving an overall strength of 6840 tons. Roebling added the stay strength of 6840 tons directly to the cable strength to arrive at a total strength of 15,264 tons. This addition would only be valid for a stay which has an angle of inclination equal to the slope of parabolic cable at the towers, where its tension is greatest. The tangent of the parabolic cable at the tower had an angle of inclination of about 19 degrees and the stays varied from about 55 degrees to 15 degrees. Roebling used the "tangent stay" as a representative angle in order to simplify calculations and avoid the need to estimate a different force for each stay. Roebling rounded up the strength of 15,264 tons to 16,000 tons to account for the additional efficiency of the stays within the tangent line of the parabolic cable at the towers. Roebling calculated the safety factor for dead load to be 8; for dead load plus extreme live load, 6.2; and for dead load plus typical live load, 7.2. By including the stays in the estimation of the vertical strength of the Cincinnati Bridge, the safety factors were larger than for the suspension cables alone.

Although Roebling never cited the percentage of total load he assumed the stays to carry, that value can be estimated. If the bridge fails in a ductile manner, each stay will have an axial force equal to its strength, and the vertical component of that force will vary based on the stay inclination. Based on a tangent stay inclination of 19 degrees, the stay strength of 6840 tons corresponds to a total vertical force of about 2200 tons. Using a more typical inclination of 30 degrees, results in a total vertical capacity of about 3420 tons. A uniform vertical load of 5383 tons will create a maximum tension in the parabolic cable equal to the strength of 8424 tons (Eq. 2). Thus the vertical strength of inclined stays accounts for about 30% to 40% of the total vertical strength of the bridge, with the remaining 60% to 70% being provided by the suspension cables.[55] This load distribution between cables and stays is consistent with the values previously estimated from the unbuilt proposals.[56]

In parallel with his written descriptions, the calculations for the Cincinnati Bridge clearly represent an evolution in Roebling's conception of the stays, from a stiffening element to both a stiffening and load carrying element. Roebling ensured that the stays do in fact carry a substantial portion of the dead load by tensioning the stays during construction against the self-weight of the bridge deck. In an earlier 1846 proposal for a suspension bridge at Cincinnati, Roebling discussed tensioning the stays to relieve the vertical suspenders of their load.[57] Roebling even suggested that the main suspension cable could be designed only for the weight of the center portion of the bridge where no stays existed, although for safety and conservatism he designed the cables for the weight of the entire bridge. Roebling designed the vertical suspenders near the towers to be smaller in diameter than those near the center of the bridge "because their tension will be almost entirely relieved by the stays." [58] In the 1867 Cincinnati Bridge *Report*, Roebling wrote

> As soon as the stays are tightened, the cables will be relieved at those points, and in consequence sink in the center.[59]

Providing a substantial initial tension in the stays is essential to their effective functioning as a stiffening element for non-uniform live or wind loads. Deformations of a suspension bridge under non-uniform loads will result in some areas of the bridge deck deflecting upwards, and stays in areas where the bridge deck deflects upwards will have their total tension reduced. In order for such stays to provide resistance to deformation, they must have a sufficient initial tension in order to prevent loss of net tension due to live loads. Pre-tensioning of the stays using the dead weight of the bridge is also a Roebling innovation and was not necessarily appreciated by other suspension bridge designers. A study on the use of inclined stays in suspension bridges by other designers found that they were often used in visual imitation of a Roebling bridge. [60] Since the stays on such bridges were not designed as a load carrying element, they were likely ineffective as a stiffening elements.

Vertical Suspenders

The majority of the vertical suspenders on the Cincinnati Bridge were wire rope of 5 inch circumference spaced at 5 feet, each with a strength of 45 tons. Roebling estimated the self-weight of a 5 foot length of bridge to be 5.7 tons, and the weight of a crowd of people to be 2.4 tons. The total dead and live load of 8.1 tons was supported by 2 suspenders, one on each side of the bridge, for a resisting strength of 90 tons and a safety factor of 11. Roebling did not include any calculations related to the effects of concentrated loads from heavily laden carriages on the design of the suspenders, although such a case would be substantially less severe than the case of locomotives on the Niagara Bridge. The heaviest single vehicle load Roebling considered in calculating the live load for the main cables was 10 tons. If such a vehicle were placed near one side of the bridge and supported over a 20 foot length of bridge, then the load would be shared by 4 suspenders. The resulting force per suspender of 2.5 tons is approximately equal to the live load case considered from a crowd of people.

Stiffening Truss

As for the Niagara Bridge, the Cincinnati *Report* contained no specific details about how the members of the stiffening trusses were sized or otherwise designed. Roebling stated that their function is

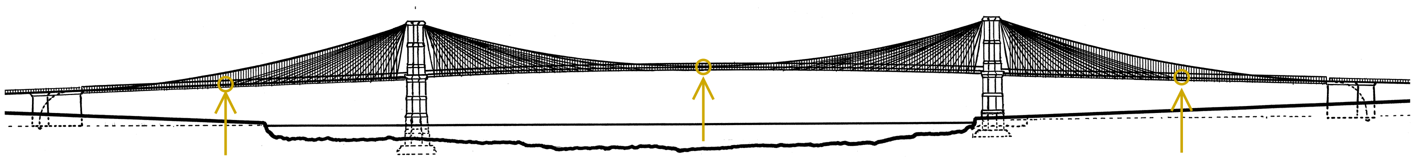
> to distribute the effects of heavy transitory weights over a greater length of floor, and also to assist in meeting the impressions made by heavy gales.[61]

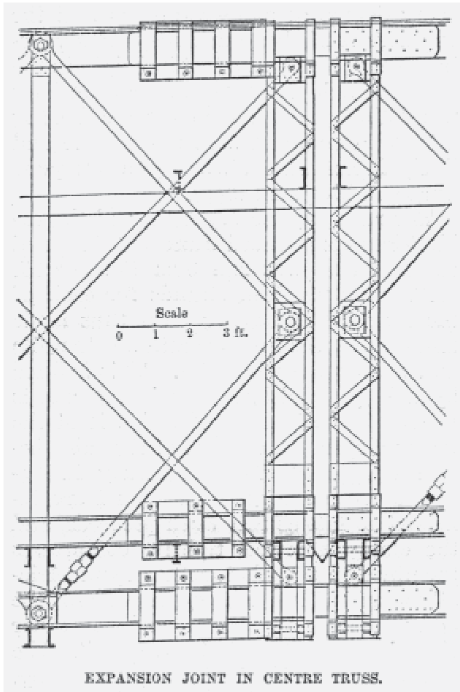
Design for Wind Loads

For design of the Cincinnati Bridge, Roebling used a maximum uplift pressure of 50 psf over the entire lower surface of the bridge, resulting in a total vertical force of 900 tons. Opposing the uplift force, Roebling included 1300 tons from the weight of the superstructure, 100 tons from the self-weight of the main cables and 500 tons uplift strength for the connections between the ends of the truss and the towers. The total resisting force of 1900 tons provided a safety factor of approximately 2, similar to that of the Niagara Bridge.

Figure 17

Locations of three expansion joints in the truss of the Brooklyn Bridge and detail of the joint [top: adapted from Historic American Engineering Record NY-18, bottom: Harper's 1883].





The Views of Washington A. Roebling

John A. Roebling's eldest son Washington (1837-1926) attended Rensselaer Polytechnic Institute from 1854 to 1857, where according to Washington the curriculum was largely based on that of the École Polytechnique in France.[62] In 1865, after serving in the Union Army during the Civil War, Washington became the assistant to his father for the construction of the Cincinnati Bridge. Washington's academic training was a frequent source of disagreement between father and son

> What I had learned at Troy did not suit him. When he could not conquer by reasoning he fell back on authority. Often he was right.[63]

After John Roebling's untimely death in 1869, Washington became the chief engineer of the Brooklyn Bridge and would see the project through its final design and construction. Later in his life Washington Roebling completed a manuscript biography of his father which was written primarily during two periods in the 1890s and a third in 1908.[64] Washington Roebling's discussions of suspension bridge design, construction and behavior from his experiences at Cincinnati and Brooklyn contrast John and Washington Roebling's conceptions of the stayed suspension bridge, and at the same time reflect a broader trend from design-based towards analysis-based structural engineering.

John Roebling's design for the truss of the Cincinnati Bridge included joints spaced every 30 feet to minimize interaction between adjacent stays and to allow longitudinal movement in the deck. Reflecting on the design of the Cincinnati Bridge, Washington described the truss and stay system

> Again the longitudinal trusses were cut up into little sections—so they failed their purpose entirely and did not act—The stays should have been discarded and continuous trusses put from anchorage to anchorage.[65]

Washington also described the great difficulty in tensioning the stays and achieving the desired balance of load between the stays and vertical suspenders.[66] In describing the original design of the Brooklyn Bridge, Washington again noted that the trusses were broken into short 30 foot sections and the practical difficulties of getting the stays and parabolic cables to act in harmony.[67] Washington eventually revised the stiffening truss design of the Brooklyn Bridge so that truss was continuous between the towers, except for a hinge or slip-joint at mid-span (Figure 17). Two additional slip-joints were located near the center of each of the side spans to reduce interaction between the portion of the side span supported by the stays and cable and the portion supported only by the cable.[68] In a suspension bridge with no inclined stays, the presence of such joints creates practical difficulties with little overall savings in truss material.[69] By the turn of the century Washington Roebling clearly acknowledged that stays were no longer the preferred engineering solution for a long span suspension bridge. In an 1896 letter to James McKee regarding a design for a suspension bridge across the Mississippi River at St. Louis, Washington Roebling recommended that the design "dispense with the stays and rely entirely on the trusses for stiffness." [70]

John Roebling's design conception of the stayed suspension bridge did not rely on the truss to transfer load to the towers; its function was to provide local stiffening to distribute concentrated loads over a greater longitudinal length of the bridge. In contrast, the statements by Washington reflect an analysis-based conception of the stiffened suspension bridge in which the continuity and bending stiffness of the truss are used to carry a substantial portion of the live loads to the towers. However, structural analysis of a truss stiffened suspension bridge was not possible until the development of a mathematical theory for stiffened suspension bridges. Washington Roebling acknowledged that the first such theory by William Rankine would not be published until several years after completion of the Niagara Railroad Bridge.[71] Further the Cincinnati and Brooklyn Bridges were well beyond the scale at which the Rankine's theory gives accurate results.[72] However once the mathematical theories of stiffened suspension bridges were sufficiently developed to accurately analyze bridges at the scale of the Brooklyn Bridge, these theories would have a profound effect on the development of structural form and design of long-span suspension bridges.

Theory of Deck-Stiffened Suspension Bridges

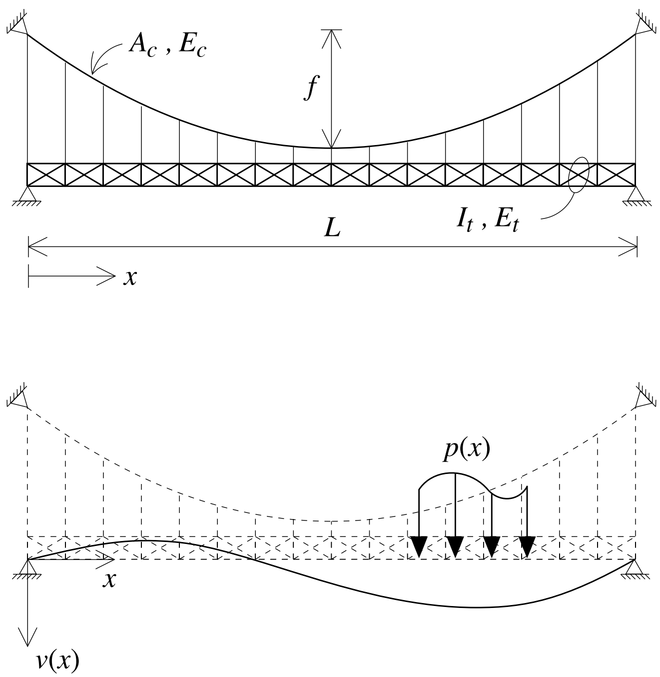
During the mid to late 19th century, deck-stiffening became the preferred method of limiting vertical motions due to live and wind loads. Prompted by the success of stiffened suspension bridges by Roebling and others, a series of three suspension bridge theories of increasing mathematical accuracy and complexity led to suspension bridges of unprecedented spans and material efficiency. These suspension bridge theories provided engineers with structural analysis tools but also confined structural design to the realm of bridge forms accommodated by the assumptions inherent in the mathematics. John Roebling's use of inclined stays would quickly disappear as mathematical analysis of highly indeterminate systems remained intractable. The only known published attempt to develop a structural analysis method for stayed suspension bridges appears to have had little influence.[73] Even Washington Roebling would consider stays unnecessary once the theoretical grounding for the deck-stiffened suspension bridge was sufficiently developed. The need for the design of a bridge to fit existing analysis capabilities is illustrated by David Steinman's 1935 proposal to "strengthen" the Brooklyn Bridge by removing the stays.[74] The following sections review the three major stiffened suspension bridge theories—Rankine, Elastic, Deflection—in order to highlight the connections between the mathematical theory and design practice.[75]

Rankine Theory

The Rankine Theory[76] assumes that the bending stiffness of the bridge deck transforms any non-uniform or local live load into a uniform upwards pull of the suspenders across the entire span. Since the suspender force is assumed uniform, the main cable

Figure 18

Deck stiffened suspension bridge subjected to live load *p(x)* resulting in deflected shape *v(x)*.



will remain parabolic in shape with a small increase in total cable sag and tension. The Rankine Theory satisfies equilibrium of the bridge deck by assuming that all of the live load is transferred to the suspension cable, but makes no attempt to satisfy compatibility of deformations between the bridge deck and the suspension cable. Rankine was aware of the lack of compatibility and comments on it. To calculate moments and deflections in the bridge deck, Rankine analyzed the deck as a simply supported beam subjected to the non-uniform live load and an upwards uniform suspender pull.

The Rankine Theory is a linear elastic theory, and therefore the non-linear effect of Navier's cable stiffness is not captured. A stiffened suspension bridge designed with the Rankine Theory would result in a bridge in which all of the necessary vertical stiffness to resist live loads would need to be supplied by the stiffening truss. An extremely stiff truss is necessary to satisfy the assumption that the truss can distribute a non-uniform, local live load into a uniform load over the entire length of the span. The Rankine Theory does provide an approximate analysis method by which to estimate moments and deflections of the bridge deck, and thereby a mathematical basis on which to size the stiffening truss. The Rankine Theory did not have a major influence on the design of actual bridges as the approximations in the theory limit its useful application to fairly short spans. The only known application of the Rankine Theory to the design of an actual bridge was for L.L. Buck's 1870s renewal and reconstruction of Roeblng's Niagara Railroad Bridge in which the timber truss was replaced with a metal truss.[77] By the time of its publication, many bridge designers, such as Roebling, were already building spans well beyond the limits of the Rankine Theory.[78]

Elastic Theory

Following Rankine's work a number of engineers sought to improve analysis of deck-stiffened suspension bridges by applying concepts of linear elastic, indeterminate structural analysis to satisfy both equilibrium and compatibility of deformations. The form of the Elastic Theory used in the late 19th century is most closely associated with the work of Josef Melan and is based on a parallel to deck-stiffened arches.[79] The Elastic Theory removes Rankine's simple assumption that all of the live load is transferred to the suspension cable and instead divides the live load between the cable and truss based on their relative elastic stiffnesses. The Elastic Theory assumes that the bridge deck and cable have equal vertical deformations, thus satisfying compatibility. Equilibrium is enforced on the undeformed shape, making the theory linear.

The fundamental differential equation of the Elastic Theory is

$$\underbrace{EI\frac{d^4v(x)}{dx^4}}_{\text{truss}} = \underbrace{p(x) - \frac{8hf}{L^2}}_{\text{loads}} \qquad (5)$$

where h is the horizontal component of cable tension due to the live load, $v(x)$ describes the vertical deflections, and $p(x)$ describes the live load (Figure 18). Equation (5) has two unknown quantities, h and $v(x)$. A second equation (not shown here) based on the cable shape, axial tension and elongation, relates h and $v(x)$ to the other bridge properties.

The differential equation of the Elastic Theory can be viewed as representing an unsuspended elastic beam where the applied live load of $p(x)$ has been reduced by the term $(8hf / L^2)$ due to the presence of the suspension cable. For the case of a single point load, P, at midspan, the deflection is

$$v_P = \frac{PL^3}{2048EI} \tag{6}$$

This equation has the same form as the deflection of a simply-supported beam, but with the magnitude reduced by a factor of $2048/48 \approx 43$. This observation also confirms Barlow's experimental results that showed a stiffened suspension bridge to be substantially stiffer than an unsuspended span.

With the development of Melan's Elastic Theory, suspension bridge designers for the first time had a practical structural analysis tool of sufficient accuracy that allowed them to estimate moments and deflections in the stiffening truss. Since the Elastic Theory enforces equilibrium on the undeformed structure, the non-linear effect of cable stiffness does not appear in the solution. The deflections calculated from the solution to Eq. (5) are independent of the dead load of the bridge. Although the Elastic Theory is substantially more realistic than the Rankine Theory in its load distribution between the deck and cables, it still assumes that all of the necessary stiffness is derived from the truss and none from the cable tension. Thus a suspension bridge designed by the Elastic Theory will still have a relatively heavy stiffening truss. The Williamsburg Bridge (1903) was the first major suspension bridge to be designed with the Elastic Theory, and its structural form of a deep, two-hinged stiffening truss with unsuspended side spans is a direct manifestation of the most basic formulation of the Elastic Theory. Although the main span of the Williamsburg Bridge is only 5 feet longer than that of the Brooklyn Bridge, its stiffening truss is substantially deeper (40 feet vs. 17 feet). The heavy truss of the Williamsburg Bridge is necessitated in part by its large traffic loads but also by its reliance on the truss as the sole source of stiffness. The Elastic Theory led engineers to design suspension bridges with a structural form in imitation of a mathematical theory.

Deflection Theory

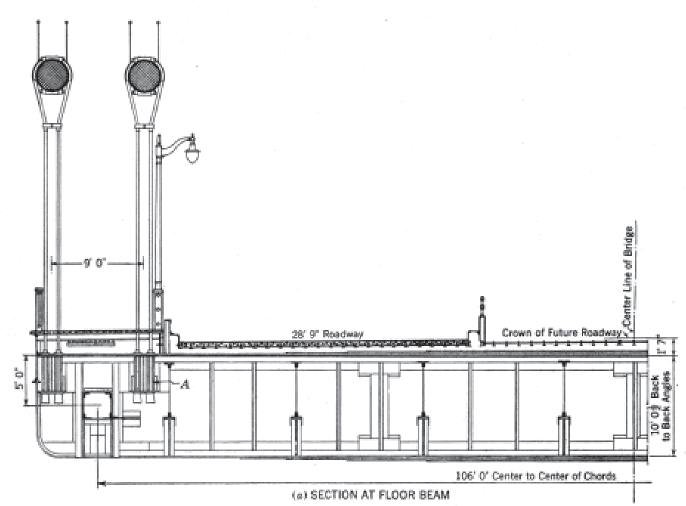
The Deflection Theory was published by Josef Melan in 1888 alongside the simpler Elastic Theory.[80] The more accurate Deflection Theory rapidly supplanted the Elastic Theory, as bridge spans had already reached the practical limits of the Elastic Theory and engineers discovered the great efficiency inherent within the complex mathematics of the Deflection Theory. The Deflection Theory enforces equilibrium on the deformed shape of the cable and bridge deck and thereby reintroduces the effect of Navier's cable stiffness. The fundamental differential equation of the Deflection Theory is

$$\underbrace{EI\frac{d^4v(x)}{dx^4}}_{\text{truss}} - \underbrace{(H+h)\frac{d^2v(x)}{dx^2}}_{\text{cable}} = \underbrace{p(x) - \frac{8hf}{L^2}}_{\text{loads}} \tag{7}$$

The second term of this equation accounts for the cable stiffness provided by the total horizontal tension force $(H+h)$ in the cable. As with the Elastic Theory, the live load tension, h, and deflected shape, $v(x)$, are unknown, and a second equation based on cable shape, axial tension and elongation is necessary. Although substantially more complex than the Elastic Theory, the differential equation for the Deflection Theory still can be solved in closed-form for many practical live load functions. The resulting solution for the deflected shape is

Figure 19

Cross-section of the George Washington Bridge as opened in 1931 with a single deck [Ammann 1933].



$$v(x) = \left[C_1 e^{cx} + C_2 e^{-cx} + \left(\frac{M'(x)}{h} - y(x) \right) - \ldots \right.$$
$$\left. \frac{1}{c^2} \left(\frac{p(x)}{h} - \frac{8f}{L^2} \right) \right] \tag{8}$$

where

$$c = \sqrt{\frac{(H+h)}{EI}} \tag{9}$$

The terms C_1 and C_2 depend on the distribution of the live load, *p(x)*; *M′(x)* is the moment function on an equivalently loaded but unsuspended beam; and *y(x)* is the initial profile of the cable. Moments in the stiffening truss are given by

$$M(x) = h \left[C_1 e^{cx} + C_2 e^{-cx} - \frac{1}{c^2} \left(\frac{p(x)}{h} - \frac{8f}{L^2} \right) \right] \tag{10}$$

The Deflection Theory provided early 20th century suspension bridge designers with a highly accurate but reasonably practical analysis method to calculate deflections and moments of the bridge deck. As a design tool, the Deflection Theory could be used to size the truss members such that strength and serviceability criteria for the bridge deck were satisfied. The Deflection Theory was first used in practice by Leon Moissieff for the design of the Manhattan Bridge (1909, 1470 foot main span), and the final report on the bridge includes an appendix by F.E. Turneaure on the Deflection Theory.[81] The Deflection Theory was subsequently used for the design of the the Delaware River (now Ben Franklin) Bridge (1927, 1750 feet) and the Detroit-Windsor (now Amabassador) Bridge (1929, 1850 feet) each of which was the longest span in the world at the time of its opening. The application of the Deflection Theory on these bridges allowed increased material efficiency in the stiffening truss, as the resistance to live load deformation due to the tension in the main cables could now be calculated. In the case of the Delaware River Bridge, Moisseiff estimated that the Deflection Theory allowed for about 35% less material in the stiffening truss of the main span.[82] Although it is possible that suspension bridge spans on the order of 2000 feet could have been designed based on the Elastic Theory, the Deflection Theory brought substantial savings and began a trend towards shallower trusses and more flexible bridge decks. By reintroducing Navier's cable stiffness, provided by the dead weight of the bridge, into the analysis of deck-stiffened suspension bridges the Deflection Theory would create a new revolution in suspension bridge design.

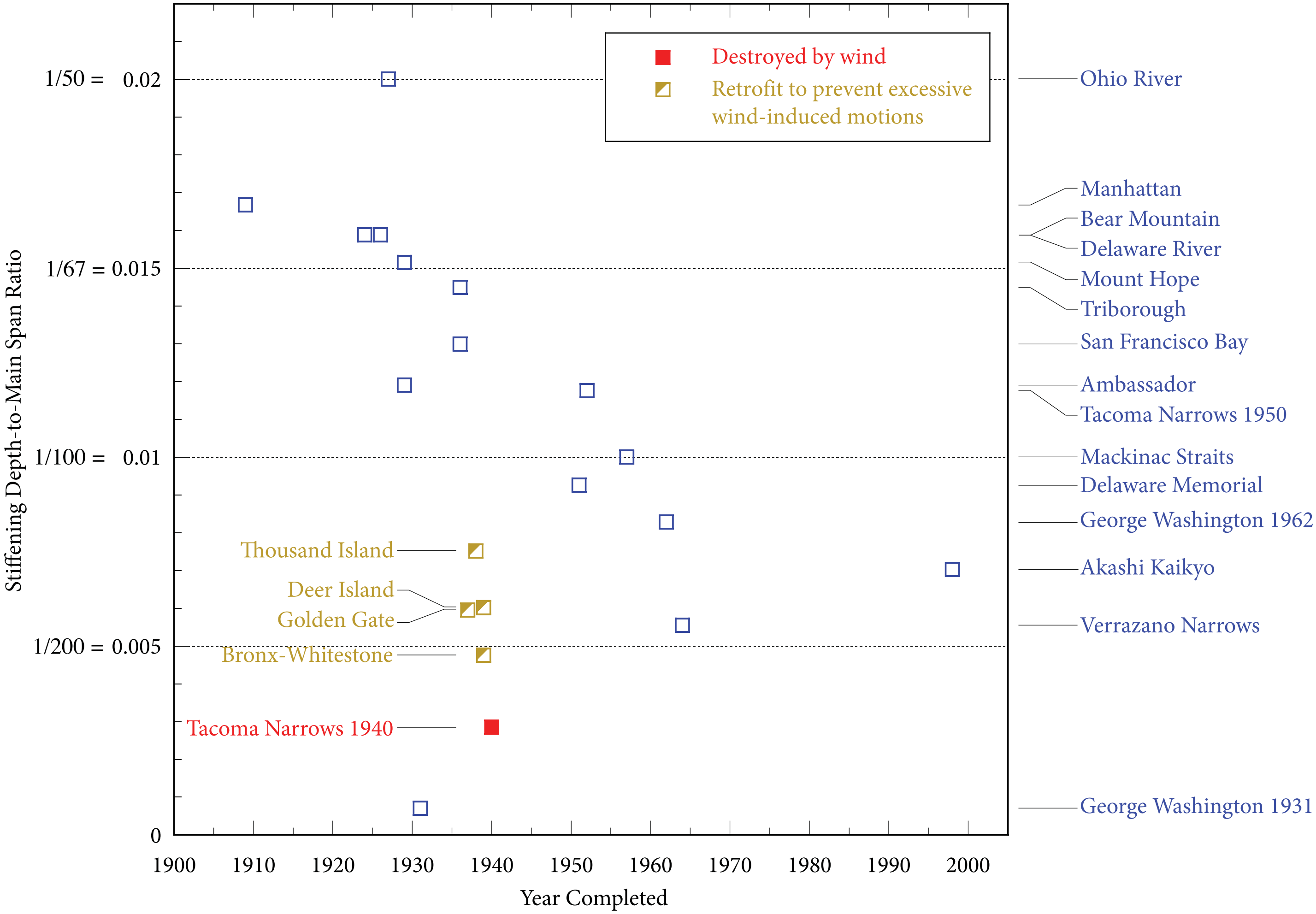
In 1931 Othmar Ammann's George Washington Bridge (Figures 19 and 20) opened with a main span of 3500 feet, nearly twice as long as the Ambassador Bridge, and only a single deck. Until the lower deck was completed in 1962, the George Washington Bridge had no vertical stiffening truss. The only continuous, longitudinal element in the bridge deck was a rectangular, built-up tube section that would eventually become the upper chord of truss for the double-deck bridge.[83] After completion of the lower deck, the truss would have a depth of 29 feet, a span-to-depth ratio of 1:120, as compared to ratios of about 1:60 for other early 20th

Figure 20

George Washington Bridge with single deck (1931-1962) and double deck (1962-present) [left: Watson Collection, Cleveland State University; right Historic American Engineering Record, NY-29-24].

Figure 21

Twentieth century trend towards more flexible decks as measured by stiffened depth-to-span ratio.



century suspension bridges (Figure 21). Ammann's bridge was an unstiffened suspension bridge, in many ways similar to the early 19th century bridges, albeit on a much greater scale. A suspension bridge needs to have sufficient total stiffness, but now there were two possible sources from which to derive that stiffness—a deck truss or the enormous tension in the main suspension cables. Ammann's calculations showed that if the bridge were large and heavy enough then all of the necessary stiffness could come from the cable stiffness, and the deck stiffness would only be necessary to limit local deformations. Ammann describes his realization of the incredible efficiency possible with the new Deflection Theory

> The permissibility of an almost flexible system in the case of the completed bridge...was not obvious to the writer at the inception of his studies.[84]
>
> As a result of lengthy theoretical investigations, supplemented by observations on mechanical models... the writer came to the conclusion that the arrangement of nearly flexible trusses in the finished bridge, and the omission of trusses in the initial stage of a single highway deck, were perfectly permissible...[85]

Rather than attempt to use the complex equations of the Deflection Theory, Amman first determined the deformed shape of the cables alone and then calculated the deck moments resulting from curvature of the deck to match the shape of the cable.[86] Amman viewed the function of deck stiffening as a means of limiting local gradients of the roadway which would otherwise follow the shape of the cable. Thus, the deck stiffening becomes a local serviceability requirement, as it was for the early 18th century unstiffened suspension bridges.

The mathematical relationship between the Deflection Theory and Navier's unstiffened bridge theory can be seen by considering the case of a large scale bridge—one with a long span and large dead load. In such a case, the deflection from Eq. (7) can be closely approximated by[87]

$$v(x) \approx \frac{h}{H+h}\left(\frac{M'(x)}{h} - y(x)\right) \tag{11}$$

And for the case of a single point load P at mid-span, the approximate deflection is

$$v \approx \left(\frac{f}{2}\right)\left(\frac{P}{W}\right) \tag{12}$$

which is identical to the deflection of the cable of an unstiffened bridge derived by Navier in Eq. (3).[88]

The Scale of Suspension Bridges: Non-Dimensional Parameters

In his 1977 paper David Billington compared the characteristics and performance of early 19th century British bridges to the early 20th century designs, including Ammann's George Washington Bridge and Moisseiff's Tacoma Narrows Bridge.[89] Although Ammann himself cited the early 19th century British bridges as influential on his conceptual design, several of the most prominent bridge designers of the late 20th century, expressed the opinion that there was simply no clear connection between bridges so widely separated in time, span and loads

> ... no one could relate [a] 19th century flimsy wooden platform hanging on parabolic cables to thousands of tons of steel an concrete.[90]

Were the flexible suspension bridges of the early 20th century any different from those of the early 19th century? Should designers have expected them to behave in a similar manner under live and wind loads? Why did many early 20th century bridges exhibit excessive wind-induced motion, while the George Washington Bridge did not, even though it has a smaller stiffening truss depth-to-span ratio? These questions are essentially ones of scale. The final section of this paper begins to address the question of scale in suspension bridges through the development and application of appropriate non-dimensional parameters, which provide a means

Table 1

Properties of Delaware River Bridge and George Washington Bridge.

Property		Delaware River Bridge (1927)	George Washington Bridge (single deck, 1931)	George Washington Bridge (double deck, 1962)	
Span	L	1750	3500	3500	ft
Sag	f	200	319.2	325	ft
Uniform dead load	w	26,000	31,590	39,500	lb/ft
Total dead load	W	45,500	110,565	138,250	kip
Live Load	p	3000	7700	7700	lb/ft
Extent of live load	m	533	360	360	ft
Equivalent point load	P	1599	2772	2772	kip
Cable area	A_c	1124	3195	3195	in2
Cable Modulus	E_c	27,000	28,000	28,000	ksi
Truss moment of inertia	I_t	1172	1.17	465.4	ft4
Truss depth	d	28	2.5	29	ft
Truss allowable stress	F_a	37,500	27,000	27,000	psi
Truss modulus	E_t	29,000	29,000	29,000	ksi

of comparing suspension bridges of widely varying physical properties and are also a convenient tool for preliminary design.

Steinman proposed a non-dimensional stiffness-factor similar to Eq. (9) which could be used to estimate the reduction in calculated moments and stresses in the deck between the Elastic and Deflection Theories.[91] Thus for preliminary design, the simpler Elastic Theory could be used and the more time-consuming Deflection Theory analysis only performed once the design was more complete. Of course this approach reinforced the notion of the Deflection Theory as a means to achieve a more economical truss design, rather than reveal the fundamental difference in behavior that Ammann recognized. Another common non-dimensional parameter used to compare the vertical stiffnesses of suspension bridges has been the stiffening member depth-to-main span ratio (Figure 21). More recently a set of two non-dimensional parameters, which measure the relative influence of cable and deck stiffness, has been proposed for use in preliminary static analysis.[92]

Based on the fundamental differential equation of the Deflection Theory (Eq. 7), a more complete set of five non-dimensional parameters can be derived.[93] The five non-dimensional parameters are

Table 2

Non-dimensional parameters for the Delaware River Bridge and George Washington Bridge.

Parameter or ratio		Delaware River Bridge (1927)	George Washington Bridge (single deck, 1931)	George Washington Bridge (double deck, 1962)
Sag-to-span	n	0.114	0.091	0.093
Live-to-dead load	γ	0.035	0.025	0.020
Dead load cable strain	ε_D	1.50×10^{-3}	1.24×10^{-3}	1.55×10^{-3}
Stiffness (as-built)	α	3.75×10^{-3}	5.18×10^{-7}	1.99×10^{-4}
Modulus	v	1.07	1.04	1.04
Allowable strain	F_a / E_t	9.48×10^{-4}	9.31×10^{-4}	9.31×10^{-4}
Truss depth-to-span	d/L	1:62.5	1:1400	1:120
Elastic moment	a	0.054	0.054	0.054
Truss-to-elastic inertia	$I_t / I_{elastic}$	2.21	0.007	0.240
Elastic stiffness	$\alpha_{elastic}$	0.017	7.41×10^{-5}	8.29×10^{-4}

Sag-to-span ratio $$n = f/L \tag{13}$$

Live load-to-dead load ratio $$\gamma = P/wL \tag{14}$$

Dead load cable strain $$\varepsilon_D = wL/A_cE_c \tag{15}$$

Deck-to-cable stiffness ratio $$\alpha = I_t/A_cf^2 \tag{16}$$

Modular ratio $$\nu = E_t/E_c \tag{17}$$

Each of these non-dimensional parameters has a clear physical interpretation, and several have already been shown to be relevant in the behavior of suspension bridges. The sag-to-span ratio (n) measures the shape of the cable and is directly related to the maximum tension force in a parabolic cable. The live-to-dead load ratio (γ) is proportional to the live load deflections of an unstiffened cable, as shown by Navier's deflection equation. The dead load strain (ε_D) is the strain which would occur if the total dead load were applied in a purely axial manner. The non-linear cable stiffness in a suspension bridge depends on the dead load strain in the cable. Further the value of ε_D does not vary widely across typical suspension bridges if the cable area is efficiently sized. The stiffness ratio (α) measures the relative influence of the deck to cable stiffness; a large value corresponds to a very stiff deck and a small value to a very flexible deck. The modular ratio (v) is necessary since in many cases the modulus of steel bridge cables is slightly less than that for structural steel used in the stiffening truss.

The stiffness ratio will be used to demonstrate how use of these non-dimensional parameters contributes to understanding the widely differing types of behavior that can be expected in suspension bridges and how the use of a particular analysis method during design constrains the bridge to a specific region of that behavior. The response of the Delaware River Bridge and the George Washington Bridge, with both one and two decks, will be considered. The relevant bridge properties and non-dimensional parameters appear in Tables 1 and 2. For simplicity, the live load case of a single concentrated load at mid-span will be considered, although this is not typically a controlling live load case for

Figure 22

Effect of stiffness ratio on deflection and moment due to concentrated live load at mid-span: Delware River Bridge.

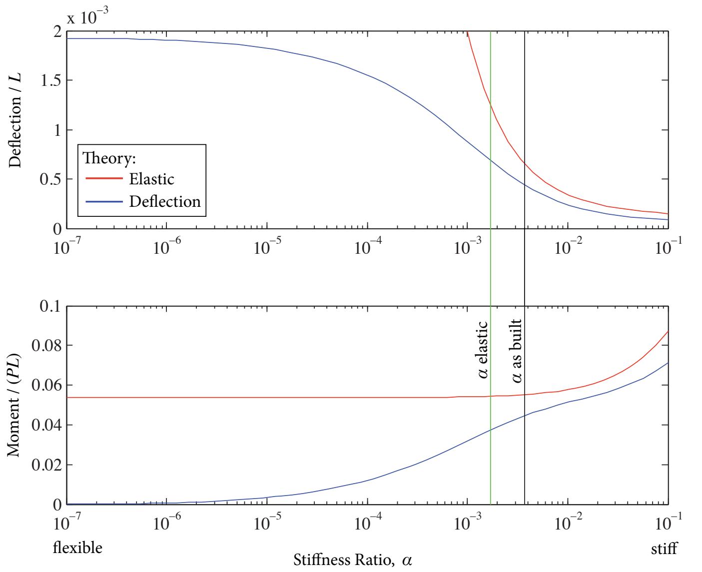
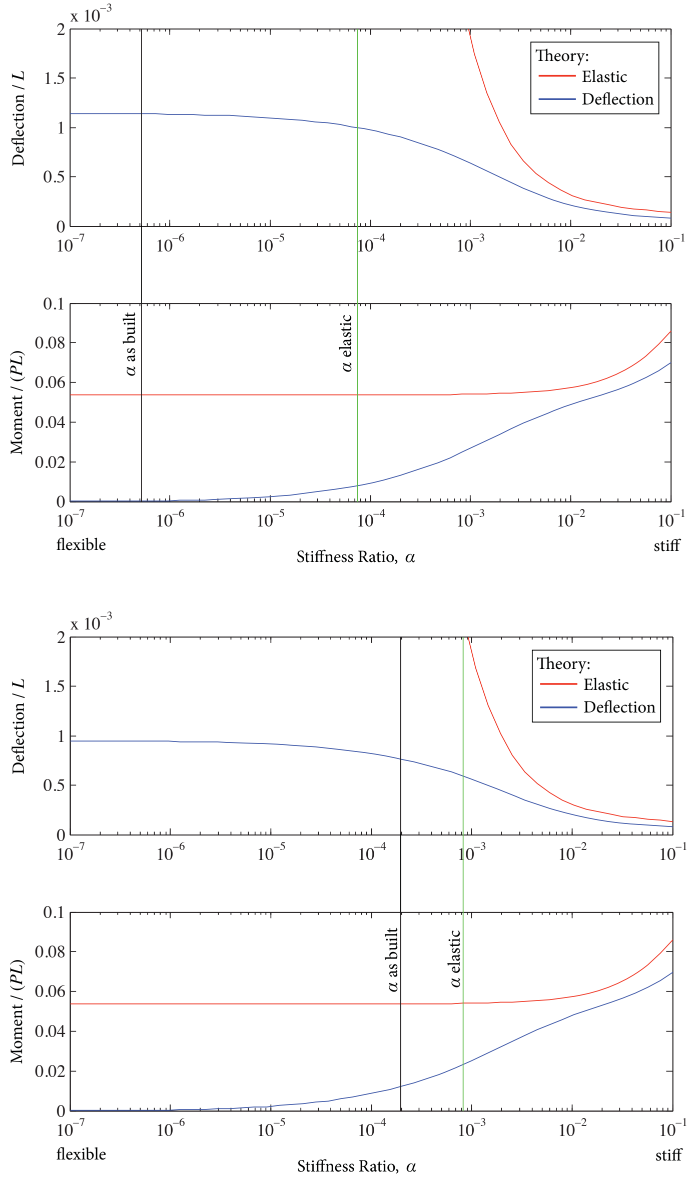


Figure 23

Effect of stiffness ratio on deflection and moment due to concentrated live load at mid-span: George Washington Bridge with *single-deck* (top) and *double-deck* (bottom).



suspension bridge design. Figures 22 and 23 show the maximum moments and deflections across a wide range of stiffness ratios, as determined by both the Elastic and Deflection Theories, with the vertical black line indicating the value of α for the bridge as-built.

In all three cases, as the stiffness ratio is decreased towards zero (corresponding to an extremely flexible deck), the moment as calculated by the Elastic Theory plateaus to a minimum value. For a design based on the Elastic Theory, this moment represents the minimum possible design moment for the truss, or

$$M_{elastic} = aPL \tag{18}$$

where the numerical coefficient a depends on the particular distribution of live load. If the stiffening truss has a depth, d, between chords and the chords have an allowable stress of F_a, then the required truss moment of inertia is

$$I_{elastic} \geq \frac{aPLd}{2F_a} \tag{19}$$

Setting I_t equal to $I_{elastic}$ in Eq. (16) and solving for α, the resulting value of the stiffness factor is

$$\alpha_{elastic} \geq \left(\frac{a}{2}\right)\left(\frac{\gamma\varepsilon_D}{\nu n^2}\right)\left(\frac{d}{L}\right)\left(\frac{E_t}{F_a}\right) \tag{20}$$

where d/L is the ratio of truss depth to span length and F_a/E_t can be interpreted as the allowable strain. This limiting value of $\alpha_{elastic}$ is plotted as a vertical line in Figures 22 and 23. In the case of the Delaware River Bridge, the smallest possible truss moment of inertia using the Elastic Theory constrains the bridge to the region of the design space which contains relatively stiff decks. In this region, use of the Deflection Theory provides a material savings but not a fundamental change in behavior or efficiency, as was recognized by Ammann. Further, use of the type of stiffness factor proposed by Steinman, in which Elastic Theory results are reduced by a certain percentage, will never reveal to the designer the fundamental change in behavior that occurs below a certain threshold of the stiffness ratio.

The analysis of the George Washington Bridge demonstrates that as the stiffness factor decreases, the deck moments continue to decrease, while the deflections approach a limiting value corresponding to the case of the unstiffened cable. This behavior corresponds to Ammann's observations that acceptable deflections can be achieved through cable stiffness alone and deck stiffness is only necessary to control local deflections and gradients of the deck.

The Deflection Theory and Ammann's design for the George Washington Bridge had a significant influence on the trend towards more flexible bridges built during the 1930s (Figure 21). The amount of vertical stiffening required by the Deflection Theory became so small that plate girders were more practical and economical in place of trusses. The change from trusses to plate girders had the unintended effect of changing the aerodynamic properties of the bridges. Several notable bridges, including the Golden Gate (1937), Thousand Islands (1938), Deer Isle (1939) and Bronx-Whitestone (1939) were retrofitted to prevent excessive wind induced motion (see Figure 21). The Tacoma Narrows Bridge designed by Leon Moisseiff used a shallow plate girder (1/350th of the span) and was extremely light (5700 lb/ft self-weight). On November 7, 1940 the Tacoma Narrows Bridge was destroyed due to wind-induced oscillations in a manner that was eerily similar to the failures of the early 19th century English bridges or the Wheeling Bridge. The failure of the Tacoma Narrows Bridge initiated a major engineering inquiry that ultimately led to the development of the field of aerodynamics of structures.[94]

The fundamental shortcoming of the Deflection Theory was that it created a reliance on cable stiffness as the sole source of stiffness. While cable stiffness is effective in resisting deformations due to live loads, it is entirely ineffective in resisting purely anti-symmetric deformations, such as those typically induced by aerodynamic forces.[95] For the Tacoma Narrows Bridge, anti-symmetric motions of an amplitude of approximately ±24 inches can be produced by an anti-symmetric load of only 5 psf.[96] In designing the Niagara and Cincinnati Bridges, John A. Roebling used a design wind pressure of 50 psf. Roebling used the inclined stays to ensure that the entire bridge deck acted in unison, preventing any anti-symmetric deformations of the type observed in the 19th century bridge failures and commented on by engineers such as Russell. Rather than using complex analysis methods to create structures which behave in an unclear manner, Roebling used structural design concepts to create structures which behaved in a manner that he was able to analyze with simple and direct analysis methods.

Conclusions

The development of suspension bridges during the 19th and early 20th centuries illustrates the interaction of practice and theory, and the contrast between design and analysis in structural engineering. *Design* is an intellectual process used to develop the form and details of a structure and demonstrate that it meets criteria such as safety and serviceability. Structural *design* relies on fundamental principles such as strength, redundancy and ductility. *Analysis* estimates response of a given structure but is only one tool within the process of structural design. The information provided by analysis is not sufficient to achieve successful design, and such knowledge may constrain the region of the design space considered by the structural engineer.

The two fundamental structural design issues for a suspension bridge are: first, to provide suspension cables of sufficient strength; and second, to limit deformations of the bridge deck to provide serviceable passage. Early 19th century suspension bridges consisted of little more than an unstiffened deck hung from cables or chains. For such a bridge, there is a close correspondence between the built form and the mathematical idealization, or between design and analysis. The initial application of structural analysis to the design of suspension bridges was the development of a mathematical relationship between the suspended weight of the bridge and the maximum axial force in the chain, allowing designers to appropriately select the cable cross-sectional area. Unstiffened suspension bridges were notorious for exhibiting excessive deflections due to passing live loads and wind forces, and control of these motions became a primary design objective. The work of Navier provided the mathematical formulation for the concept of non-linear cable stiffness and the analytical tool through which designers could control vertical live load deflections. Reflecting Navier's influence, Ellet's Wheeling Bridge employed a shallow cable profile and a heavy, but flexible, deck in order to provide vertical stiffness. Nevertheless, nineteenth century suspension bridges continued to exhibit susceptibility to excessive wind-induced motions. A variety of practical methods of stiffening suspension bridges were employed, including trusses, inclined stays and reverse cables. All of these stiffening methods transformed the suspension bridge from a simple cable to an indeterminate structural system.

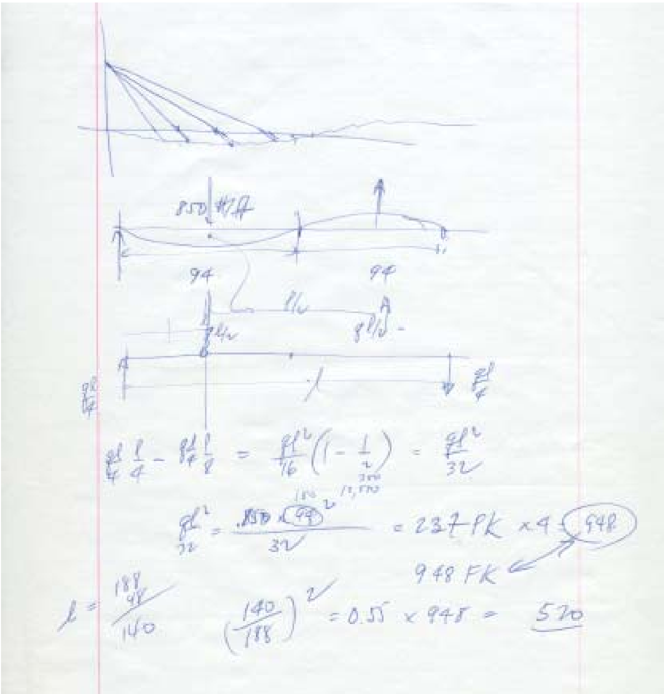
John A. Roebling superimposed three structural systems---parabolic cables, inclined stays and stiffening trusses---to achieve bridges of unsurpassed span and performance. Roebling's writings and calculations reveal an evolution in his conception of the role of the inclined stays from purely a supplementary stiffening element to a primary load carrying element. Roebling also used the stays to provide wind resistance by forcing the bridge deck to act in unison by preventing antisymmetric deformations. The complex and highly indeterminate nature of Roebling's system made structural analysis, in the modern sense, simply impossible. Yet Roebling developed an innovative design method based on fundamental structural principles of strength, redundancy and ductility as reflected in his writings and published design calculations published for the Niagara Railroad Bridge and Cincinnati Bridge. Roebling's design methods rely on many of the same fundamental principles as modern strength and performance-based design methods.

The success of Roebling's bridges directly stimulated the development of the Elastic Theory of the suspension bridge, in which the only source of stiffness was the deck truss. The ability to perform structural analysis of a deck-stiffened suspension bridge contributed to the disappearance of inclined stays. The inclusion of stays rendered the structural analysis many times indeterminate and intractable, whereas a deck stiffened bridge could be readily analyzed and designed to perform successfully. The stiff decks of these bridges were sufficient to prevent wind-induced motions even without stays. The non-linear deflection theory of suspension bridges reintroduced the effect of cable stiffness, and Ammann's George Washington Bridge demonstrated that cable stiffness alone could provide sufficient overall stiffness to resist live loads.

The design of early 20th century bridges quickly returned to the unstiffened forms of the early 19th century bridges, as influenced by the Deflection Theory. The reliance solely on cable stiffening ultimately would lead to the dramatic failure of the Tacoma Narrows Bridge and the revelation that cable stiffness is not effective in resisting wind-induced deformations. Thus the design of the built form of suspension bridges in the early 20th century was constrained by Navier's straightjacket—limited to those forms that could be analyzed with current theoretical tools—without

Figure 24

Notes on the behavior of a stayed suspension bridge by David Billington, April 3, 1991.



proper consideration of more fundamental structural design concepts.

The tension between design and analysis is not unique to suspension bridges, and is a critical component to the idea of structural art, as documented by David Billington through the work of Robert Maillart, Heinz Isler and others.[97] For many of the best structural artists, such as Roebling, discipline was not provided by the capabilities of structural analysis but rather by the application of fundamental design principles such as strength, redundancy and ductility. The development of modern, indeterminate structural analysis led to an increasing emphasis on the tool of *analysis* to the detriment of the discipline of *design*. Structural design was constrained within the space of structures that could be analyzed with currently available analysis tools. The development of modern computerized, non-linear structural analysis may have removed the constraints of Navier's straightjacket, allowing willfully complex structural systems to be proposed and built. Yet it remains to be seen if the structural engineering profession can use the potential of these powerful computational analysis tools in the context of design. Even for complex structural systems, the application of the principles of strength, redundancy and ductility are critical to structural design and provide fundamental insights into structural behavior, distinct from those of structural analysis. These principles remain relevant to the structural engineering profession today and can provide conceptual clarity in the structural design process.

Acknowledgements

The research presented in this paper began in the fall of 1990 with my undergraduate thesis at Princeton University under the guidance of David Billington. The opportunity to work one-on-one with David Billington over the course of my senior year and to immerse myself in a research problem was a singular and transformative experience in my career and life. Our learning together over that year was captured in pages of skecthes, notes and equations written by David, some of which he handed me while others remain in one of his numerous spiral-bound notebooks (Figure 24).

The breadth and depth of knowledge developed during that year have allowed me to continue to conduct new research in this area for more than two decades. Working side-by-side with David Billington taught me much about structural design, but equally important about how to conduct research, to teach and to advise students. David Billington taught me how to *think structures*.

The idea of relating Roebling's design methods to modern strength design methods has its roots in a brief but insightful comment from Paul Gauvreau after a presentation I made at David Billington's 80th birthday symposium in 2007. John Ochsendorf first exposed me to the work of Jacques Heyman, which has been crucial in the development of my thinking on the nature of design as distinct from analysis. Previous collaborations with Dario Gasparini have been instrumental to my understanding of the behavior of cable structures and the use of non-dimensional parameters in their analysis. The author gratefully acknowledges the support provided by The Rooke Chair in the Social and Historical Context of Engineering.

Notation

The following symbols are used in this paper:

a = minimum moment coefficient for Elastic Theory;
c = Deflection Theory exponential parameter;
d = chord-to-chord depth of stiffening truss;
f = cable sag;
h = increase in horizontal component of cable tension due to live load;
n = sag-to-span ratio;
$p(x)$ = live load as a function of position;
v = vertical deflection at mid-span;
$v(x)$ = vertical deflection as a function of position;
w = dead load per unit length;
x = position on bridge measured from left-support;
$y(x)$ = initial shape of parabolic cable;
C_1, C_2 = Deflection Theory integration constants;
E_c = cable modulus;
E_t = truss modulus;
F_a = allowable stress of stiffening truss;
H = horizontal component of cable tension due to dead load;
$I_{elastic}$ = minimum truss moment of inertia for Elastic Theory;
I_t = truss moment of inertia;
L = length of main span;
$M_{elastic}$ = minimum design moment for Elastic Theory;
$M(x)$ = moment in deck as a function of position;
$M'(x)$ = moment in simply supported beam as a function of position;
P = concentrated live load;
T = maximum cable tension, occurring at ends;
W = total dead load (= wL);
α = stiffness ratio;
$\alpha_{elastic}$ = minimum stiffness ratio for Elastic Theory;
γ = live-to-dead load ratio;
ε_D = dead load cable strain; and
ν = modular ratio.

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THE FOURTH "E"
THE ENVIRONMENTAL DIMENSION OF STRUCTURE

Powell Draper and Edward M. Segal

Introduction

One of the most under-appreciated legacies of Professor David Billington is his use of travel as a scholarly tool. His lectures are peppered with photographs of works of structural art not from books but from his personal pilgrimages to them. He displays his enthusiasm for structures as art throughout his lectures, but develops a particular glint in his eye when mischievously relaying a story of trespassing to get just the right shot of a connection detail on Eiffel's Garabit Viaduct. And nothing wakes up a darkened lecture hall full of drowsy students quite like hearing their esteemed professor tell them about the time he was nearly blown up by a live-fire drill conducted by the Swiss army while he was photographing a nearby bridge.

But Professor Billington does not limit this enthusiasm for in-person visits to works of structural art to himself. He has, over the years, generously provided for many of his students to travel to particular structures as a part of their research (the authors included). Three of his students (Chelsea Honigmann, Edward Segal, and Ashley Thrall) have won the SOM Foundation Structural Engineering Travel Fellowship. And many more (including students of his students) have made their own pilgrimages to see the great works about which he has taught us. And on occasion his students and others, as well, have documented not just the visit but also their interpretation of the meaning of travel to structures.[1, 2]

In our attempts to carry on what Professor Billington has taught us, we have sought to learn from and expand this emphasis on travel to appreciate not just the structures themselves, but also how visiting them can enhance structural engineering research, education, and outreach. This suggests that Professor Billington's three dimensions of structure—efficiency, economy, and elegance[3]—might be expanded to include *environment*.

Research: Site and Sight

In 2010 we began a project to catalogue and study the bridges in a particular region, in this case the bridges crossing the Hudson River, to see what we c find about the relationship of bridges to both the natural and built environments.

The Hudson River defines a historically rich region. It is also home to a variety of bridge types that reflect the development of structural engineering. For this project we catalogued the existing bridges crossing the Hudson River to determine what they can teach us about the history of structural engineering, structural forms for bridges, and the relationships bridges have to their environments and to the other bridges nearby.

A recent book describes the history of many of the bridges on the Hudson.[4] This study was not intended to cover territory already described in that work or in others.[5, 6, 7] Instead we aimed to show how the forms of the Hudson River Bridges vary with respect to geography, chronology, span, and site. Looking at the bridges through these lenses suggests that how a bridge relates to its specific environment is not always a significant consideration of designers when selecting a form.

An area of particular focus is the Tappan Zee Bridge, built in 1955. This bridge and the plan for its replacement have been the topic of several local news articles.[8, 9] But nearly all of the public and political discussion has focused on the cost of replacing the bridge and not on how the bridge might make a positive addition to its surroundings. A consideration of the relationship between the location of the replacement bridge to its form may contribute to a new look at how we should go about replacing the bridge. Notable academics and bridge designers have identified the relationship of a bridge's form to its environment as one important criterion by which we can critique bridge aesthetics. By describing the opinions of these experts we intend to show the significance of this aspect of a bridge's design. To further demonstrate the influence of a bridge's integration into its environment on its overall aesthetics, it is necessary to compare two bridges in which everything but the environment is held constant. A case study comparison of two nearly identical bridges by Robert Maillart reveals this influence and provides the means to extrapolate to future comparisons between Hudson River Bridges where more than the environment varies.

Looking at the form of bridges in relation to their locations proves to have educational benefits as well. A catalogue of local bridges provides examples for students to better understand how structures are designed, analyzed, constructed, and maintained. Visits to built works can be used to augment traditional methods of teaching structural design and analysis. In this way we can also give students a sense of the social and symbolic contexts of structures, in addition to the technical.

The Hudson River Bridges

Geographic Progression

The Hudson River flows for more than three hundred miles along eastern New York from the Adirondacks to New York City. Here we have focused on the major portion of the Hudson from New York City to where the Mohawk River feeds into it north of Troy, as this defines the main area of industrial growth along the Hudson.

Table 1 shows the geographic order of bridges crossing the Hudson. We see a general variety of types of forms, with nearly all major bridge types represented save for arches and cable stayed. The bridges also include a variety of spans, from smaller spans on the order of 60 m (194 ft) for the bridges in Troy, where the Hudson is narrower, to the 1,100 m (3500 ft) span of the George Washington Bridge.

Chronological Progression

Table 2 shows the chronological progression of bridges on the Hudson. Many bridges on the Hudson have been destroyed or replaced over the years. This table shows only existing bridges.

Here we see a correlation between the era of the bridge and its form. The earliest bridges up until the 1920s were trusses, as we might expect in accordance with the historical development of bridge engineering in this country. The 1920s saw the construction of three suspension bridges, followed by a return to trusses. The late 1960s show a move toward beam bridges.

The eighteenth and nineteenth bridges in the table each represent special cases. The Newburgh-Beacon Bridge #2 of 1980 was designed as a twin to the Newburgh-Beacon Bridge #1 of 1963.[10] And the Green Island Bridge is a vertical lift bridge for its original railway loading, but is also of the beam type.

Thus we see in essence four eras of bridge types for the crossings of the Hudson: truss, suspension, truss again, and beam. This suggests a tendency to follow historical trends when selecting a bridge type.

Span length

The relationship between the form of the bridge and its span length (as well as construction considerations) has been well documented. For example, the manual *Design of Modern Highway Bridges* states, "Only certain types of structural forms are suitable and economically viable alternatives for certain span ranges."[11] Table 3 shows the type and span length of selected bridges on the Hudson. The information for some of the other bridges has not yet been confirmed, but many of the beam bridges are of visibly shorter span and length (i.e. narrower sections of the Hudson). Span length along with the cost of design and construction plays a large role in the choice of an appropriate type of bridge.[12]

Table 1

Geographic order of bridges crossing the Hudson River.

		Bridge	Year	Type
1	N	Troy-Waterford	1909	Truss
2		112th Street	1996	Beam
3		Collar City	1980	Beam
4		Green Island	1981	Beam
5		Congress Street	1971	Beam
6		Troy-Menands	1933	Truss
7		Patroon Island	1968	Truss (deck)
8		Livingston Avenue	1909	Truss (swing)
9		Dunn Memorial	1969	Beam
10		Castleton	1959	Truss (cantilever)
11		Alfred H. Smith Memorial	1924	Truss
12		Rip Van Winkle	1935	Truss (cantilever)
13		Kingston-Rhinecliff	1957	Truss (continuous)
14		Poughkeepsie Railroad/Walkway Over the Hudson	1888	Truss (cantilever)
15		Mid-Hudson	1930	Suspension
16		Newburgh-Beacon #1	1963	Truss
17		Newburgh-Beacon #2	1980	Truss
18		Bear Mountain	1924	Suspension
19		Tappan Zee	1955	Truss (cantilever)
20	S	George Washington	1931	Suspension

Site

The Hudson River provides a diverse group of settings for its crossings. The river defines one of the most important regions in the historical and economic development of the state and nation and the natural beauty both of the river and the surrounding valley has been widely celebrated in literature and the visual arts.

An engineer might therefore seek to design a distinctive bridge that either complements an urban environment such as Albany or New York City or is in harmony with a grand rural setting.

Table 4 shows the type of bridge in relation to the approximate combined population of the two communities each connects. This is somewhat open to interpretation, as many of the bridges connect smaller towns that are considered parts of either the New York City metropolitan area (population of 19,000,000) or Albany metro area (850,000). But it nevertheless seems to suggest that for

Table 2

Chronological order of existing bridges crossing the Hudson River.

	Bridge	Year	Type
1	Poughkeepsie Railroad/Walkway Over the Hudson	1888	Truss (cantilever)
2	Troy-Waterford	1909	Truss
3	Livingston Avenue	1909	Truss (swing)
4	Alfred H. Smith Memorial	1924	Truss
5	Bear Mountain	1924	Suspension
6	Mid-Hudson	1930	Suspension
7	George Washington	1931	Suspension
8	Troy-Menands	1933	Truss
9	Rip Van Winkle	1935	Truss (cantilever)
10	Tappan Zee	1955	Truss (cantilever)
11	Kingston-Rhinecliff	1957	Truss (continuous)
12	Castleton	1959	Truss (cantilever)
13	Newburgh-Beacon #1	1963	Truss
14	Patroon Island	1968	Truss (deck)
15	Dunn Memorial	1969	Beam
16	Congress Street	1971	Beam
17	Collar City	1980	Beam
18	Newburgh-Beacon #2	1980	Truss
19	Green Island	1981	Beam
20	112th Street	1996	Beam

most areas, with multiple bridge types across varying populations, that the size of the localities to be connected does not heavily influence the choice of form.

One possible exception to this lack of connection between bridge form and locality is the George Washington Bridge, in New York City. Othmar Ammann, the designer of the bridge, certainly chose a suspension design as one of the few effective options based on the massive span of the structure. But he also expressed an interest in the relationship between the form and the aesthetics of the bridge and designed the bridge with an eye towards attractiveness.[15] He could have chosen the form to have his bridge complement not only its urban location, but also the other existing suspension bridges of New York City.

The Tappan Zee Bridge

In looking at the collected bridges of the Hudson River, the Tappan Zee Bridge presents an interesting individual case study

Table 3

Type and span length of selected Hudson River bridges.[13]

	Bridge	Year	Type	Span Length m (ft)
1	Troy-Waterford	1909	Truss	59 (194)
2	Poughkeepsie Railroad/Walkway Over the Hudson	1888	Truss (cantilever)	167 (548)
3	Rip Van Winkle	1935	Truss (cantilever)	244 (801)
4	Kingston-Rhinecliff	1957	Truss (continuous)	244 (801)
5	Newburgh-Beacon #1	1963	Truss	305 (1001)
6	Newburgh-Beacon #2	1980	Truss	305 (1001)
7	Tappan Zee	1955	Truss (cantilever)	370 (1214)
8	Mid-Hudson	1930	Suspension	457 (1499)
9	Bear Mountain	1924	Suspension	498 (1634)
10	George Washington	1931	Suspension	1067 (3500)

(Figure 1). It is the first bridge north of New York City and connects two historic towns, Nyack and Tarrytown, considered part of the New York City metropolitan area. Despite its location and heavy use, it is not a celebrated bridge like the George Washington. In his book on the history of bridge design, the bridge designer David Steinman (with co-author Sara Watson) stated that engineers of the New York State Thruway Authority referred to it as "one of the ugliest bridges in the East."[16]

Its current state of decay has led engineers and political leaders to decide to replace it. The appealing location, from both standpoints of natural environment and built environment, suggests an opportunity to replace the Tappan Zee with a more attractive form. As recently as 2009, an article optimistically stated that for the replacement, "transportation officials decided to think big" with plans for a bridge that would also carry rail lines.[17] Since that time economic concerns have gradually eroded the wish list to the point that the state is even considering privatization of the project just to get something built.[18] Lately almost all public discussion of the replacement has focused on the cost of the replacement bridge instead of how it might (or might not) complement its location or the other bridges of the Hudson.

Relationship of Bridge Aesthetics to Site

The importance of engineers designing bridges with an aesthetic intent, including how a bridge relates to its location, has been explained in a number of sources. Elizabeth Mock suggested that bridges be subjected to the same standards of architectural evaluation as buildings.[19] Professor Billington instead describes structural engineering as a separate creative discipline from architecture and explains that the best works of structural engineering, or structural art, are those that fully integrate efficiency, economy, and elegance.[20] Frederick Gottemoeller outlines specific prescriptive factors for bridge aesthetics, and includes suggestions on how engineers might go about improving their aesthetic design skills for all bridge designs.[21]

Others have suggested that the aesthetic qualities of bridges may be considered optional depending on cost. The Swiss bridge designer Christian Menn has described the relationship of aesthet-

Table 4

Approximate combined current population of localities connected by Hudson River bridges.[14]

	Bridge	Year	Type	Population of localities
1	Rip Van Winkle	1935	Truss (cantilever)	8,000
2	Tappan Zee	1955	Truss (cantilever)	10,000
3	Castleton	1959	Truss (cantilever)	10,000
4	Kingston-Rhinecliff	1957	Truss (continuous)	20,000
5	Poughkeepsie Railroad/Walkway Over the Hudson	1888	Truss (cantilever)	30,000
6	Mid-Hudson	1930	Suspension	40,000
7	Newburgh-Beacon #1	1963	Truss	40,000
8	Newburgh-Beacon #2	1980	Truss	40,000
9	Collar City	1980	Beam	50,000
10	Bear Mountain	1924	Suspension	50,000
11	Troy-Waterford	1909	Truss	50,000
12	Alfred H. Smith	1924	Truss	50,000
13	Troy-Menands	1933	Truss	50,000
14	Green Island	1981	Beam	50,000
15	Congress Street	1971	Beam	60,000
16	112th Street	1996	Beam	60,000
17	Dunn Memorial	1969	Beam	100,000
18	Patroon Island	1968	Truss (deck)	100,000
19	Livingtson Avenue	1909	Truss (swing)	100,000
20	George Washington	1931	Suspension	8,000,000

ics and economy, with aesthetics the center goal on a target for designers that also includes increasing rings of economy, serviceability, and, ultimately, the largest ring of safety.[22]

The German bridge engineer Fritz Leonhardt issued a series of "Guidelines for Aesthetic Structures," that includes their "Integration into the Environment."[23] Similarly, Menn, in his article, "Aesthetics in Bridge Design," states that both "integration of the bridge into its surroundings" and "design of the bridge as a structure itself" are fundamental to creating an aesthetically pleasing design.[24] In Menn's opinion, careful consideration of road lines, topography, and proportion of a structure and its components relative to its environment is necessary to create an elegant design.

Comparing Robert Maillart's Salginatobel (1930) and Rossgraben (1932) bridges illustrates the influence of site on aesthetics (Figures 2 and 3). Both are single-lane, three-hinged, hollow

Figure 1

Tappan Zee Bridge.

box arches with simple cross walls and maximum depth at their quarterpoints. Rossgraben has a slightly greater span-to-rise ratio (8.6 vs. 6.9), but otherwise, the "design of the bridge as a structure itself" is the same. While a clear evolution of form is evident when comparing Maillart's earliest to final three-hinged hollow arches, many of his intermediate bridges are similar. Jörg Schlaich in his article, "The Bridges of Robert Maillart," states:

> There is an uneasy feeling about one's inability to understand Maillart's much praised individualistic topographic relationship in view of the fact that his three-hinged arches differ from each other only marginally, contrary to their particular environments. Is the Salginatobel Bridge's major asset its environment, as opposed to the lesser known – though almost equal and cleaner – Rossgraben Bridge? Must Maillart be confronted with his own holistic postulate?[25]

Schlaich suggests that Maillart did not always conceive of a bridge form specifically for a site, but rather used the same

Figure 2

Salginatobel Bridge.

form repeatedly despite different surroundings. While neither the Salgtinatobel nor the Rossgraben is out of place in its environment, the former does benefit from its dramatic site. It is interesting to note that the Salginatobel Bridge is Maillart's only work that has been recognized as an International Historic Civil Engineering Landmark by The American Society of Civil Engineers and is arguably Maillart's best known work. The structural similarities of the two bridges cause us to question the role of site in our appreciation of the form of the bridge.

Maillart's bridges demonstrate how at times, even aesthetically sensitive engineers rely on similar forms. One could make a persuasive argument that, given the opportunity to have a bridge as elegant as Salginatobel, any owner, designer, or member of the public would gladly take a facsimile of that bridge regardless of location. In the case of Rossgraben we return to Schlaich's question and acknowledge that it may be that the arch is the best form for the site and that the environment does not stand up to Salginatobel's environment. Duplicating even the most attractive bridges in differing locales may suggest a lack of consideration

Figure 3

Rossgraben Bridge.

of the particulars of site and the possibilities therein for allowing site to contribute to form and vice versa. Standard truss and beam bridges are used at a greater frequency across an even larger array of sites with less consideration for their surroundings.

Site and Sight

The Hudson River is home to a variety of bridge types, with many of the major forms (save for arch and cable stayed) spread along the length of the river. Yet aside from the George Washington, few are celebrated as great works of structure. In tabulating the dates and spans of the collected bridges of the Hudson, the data seem to suggest that as engineers we tend to choose a type of bridge based primarily on factors like span length, the predominant form of that time, and cost, more so than how the form of the bridge might complement its environment or the other bridges nearby.

The Tappan Zee presents an interesting case study for its past, present, and future. It was designed as one of several indistinct large truss bridges in the central portion of the Hudson. Now considered past its functional lifespan, it has been deemed necessary for replacement. There has been a fair amount of debate over the requirements of the replacement bridge and certainly about its cost, but there has been little public discussion about how the appearance of the replacement bridge will contribute to (or detract from) its location. This perhaps reflects the implicit perception of aesthetic qualities as add-ons to a bridge, an unnecessary luxury that cannot be afforded during times of privation. Costly recent bridges such as the Turtle Bay Sundial Bridge in Redding, California, and a replacement span for the San Francisco-Oakland Bay Bridge suggest that we as engineers have not done enough to disprove this assumption. Yet historical examples show us that this need not be the case. Othmar Ammann's design of the George Washington Bridge, for instance, was selected not just for its dramatic form, but also for its economical design.

The Hudson River region has a rich variety of natural and built environments that is ripe for site visits. Further study is required to understand how effectively the two environments in the Hudson River region interact. The sentiments of the Swiss shell builder, Heinz Isler, illustrate the internal conflict that all members of the construction industry face: "At first I was against building because I had seen how it could destroy nature. I was of two minds: on the one hand, I didn't want to be part of this destruction; on the other hand, I was fascinated by doing things very elegantly and very lightly."[26] Ultimately, the natural and built environments need to coexist. The best bridges are those that while efficient and economical are also visually interesting both on their own and in the context of the surrounding structures and landscape.

Education and Outreach: Structural Scavenger Hunts

In "On the Conceptual Design of Structures—An Introduction," Jörg Schlaich described his proposal to sue the German government or national railroad for dotting the countryside with unsightly bridges (Schlaich 1996).[27] A colleague dissuaded him on the basis that the public has little opinion on the matter. Schlaich is passionate about bridge aesthetics, but the layperson may not be. This, Schlaich is quick to point out, is a failure on the part of the profession. The current literature on aesthetics and exemplary structures is not sufficient. We need to improve how we educate the public. The University is a logical place to begin. By introducing both engineering and non-engineering students to the complex social and symbolic issues that accompany the technical challenges of structural design and construction, the profession can create ambassadors to the greater public.

The act of visiting an elegant bridge or one that complements its surroundings can have an effect that is not possible in the classroom. While photographs and small-scale models can give a sense of how a structure relates to its environment, viewing a full-scale bridge elicits a visceral response. One immediately has a sense of the social and symbolic aspects of the structure in addition to the technical. Visits to visually interesting structures provide students with a broader understanding of structural design, analysis, construction, and context.

Professor Billington is quick to distinguish structural art from architecture. Yet he is also quick to credit architects as having played an important role in establishing the importance of aesthetics in structure and in the development of the idea of structural art. The concept of travel to great works has long been an important part of architectural education but has not been as serious of a consideration in engineering education. A "grand tour" of the great works of structural art has played an important role in the development of those engineers fortunate enough to engage in such an undertaking. But more modest tours or visits to local structures can also enhance education for engineering students, attract more students to the field, and give students and potential students a better sense of what engineers actually do and the opportunities within the field to create great works.

In 2010 we organized a "Structural Scavenger Hunt" in New York City for students at Princeton University and Manhattan College. The idea grew out of a similar yet less organized version in 2007 we developed with our fellow students while at Princeton. For the 2010 version we provided a list of potential sites to registered students before the day of the event. The morning of the event we gave them pictures of structures from the list and asked them to locate, visit and photograph as many as possible. In the evening we reassembled and discussed the structures visited by looking at the teams' pictures. Moujalli Hourani, Chair of the Civil and Environmental Engineering Department at Manhattan College, provided funds for food and Milan Vatovec of Simpson Gumpertz & Heger and Ted Zoli of HNTB allowed us to begin and end in their offices, respectively.

Practicing engineers in New York City became aware of and interested in the event, and in 2011 another Structural Scavenger Hunt was held. This time the Structural Engineers Association of New York (SEAoNY) provided sponsorship and organization. Manhattan College, the American Society of Civil Engineers Metropolitan Section, and Cooper Union also provided sponsorship. Engineers from SEAoNY also accompanied teams to provide guidance and insight as they visited the structures.

In both years we surveyed the students to assess if they enjoyed the outing and whether they thought it had any impact on their studies or appreciation of structures. Feedback has been consistently good (all students enjoyed the events and thought them beneficial) but turnout has been light both times. Future versions of the event hopefully will also include a more diverse audience, to make students, potential students, and practitioners aware of the benefits of visiting structures in person.

The events were held in New York City due to our association with schools and firms in and around New York. But potentially these events could be held in many other cities and regions that are home to enough structures of visual interest. One of the other potential benefits of events such as these is the expansion of the structural art canon to new structures and designers.

Conclusion

Professor Billington has shown us how travel to see structures and works of structural art, in their environments, can be an important part of engineering education. We can and should encourage more students (or potential students) to visit structures, either on their own or through organized events such as the structural scavenger hunts. Travel to structures can also help us formulate and pursue avenues of research that can provide context to historical or contemporary developments in structural engineering, such as seeing the bridges of the Hudson River and their relationship(s) to the natural and built environment.

Professor Billington is fond of alliteration as a mnemonic device. The three dimensions of structure that he identifies—efficiency, economy, and elegance—are no doubt made easier to remember as the three "E"s. Perhaps travel to structures and efforts to understand structures in their particular context might now suggest that the three "E"s be expanded to include a fourth: *environment*. This then could encourage structural engineers to seek new ways to maximize the beneficial relationship of structure and environment.

Professor Billington, in demonstrating the idea of structural art, has made an innovative contribution to engineering. But we must work to continue that legacy and make sure that engineers will continue to have opportunities to create works of art. Our history, well documented by Professor Billington and others, demonstrates our unique ability to contribute to the built environment, and, at our best, create works of structural art. Yet we also face an uncertain future. We must acknowledge the possibility of being marginalized as large scale decisions are to be made about our past and future infrastructure, how buildings and bridges relate to the environment, and how form and structure are to coexist. Twenty-eight years ago, in *The Tower and the Bridge*, Professor

Billington eloquently sounded a warning: "While automation prospers, our roads, bridges, and urban civil works rot."[28] Unfortunately it still holds true. The field of structural engineering is at a crossroads. The best way to honor Professor Billington's legacy is for us to celebrate, and continue to create, great works of structural engineering.

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DESIGN EDUCATION FOR THE 21ST CENTURY

Paul Gauvreau

Figure 1

Fort York Pedestrian Bridge: Inclined Arch Concept (Design and image source: Montgomery Sisam Architects Inc.)

Notwithstanding a small number of impressive projects built in a given year, the practice of structural engineering in Canada and the US has been in decline since the early 1960s. Much of this can be attributed to changes in engineering education that resulted from decisions that were made fifty years ago to transform schools of engineering into scientific research establishments. Although there have been recent initiatives to create a new "design friendly" curriculum, these efforts have largely been developed by professors who do not understand the practice of design, and thus contain many elements of questionable validity. This article proposes a definition of engineering design that is a faithful representation of the way design is actually practiced. This definition is used to develop principles on which can be based the creation of an effective curriculum for design education.

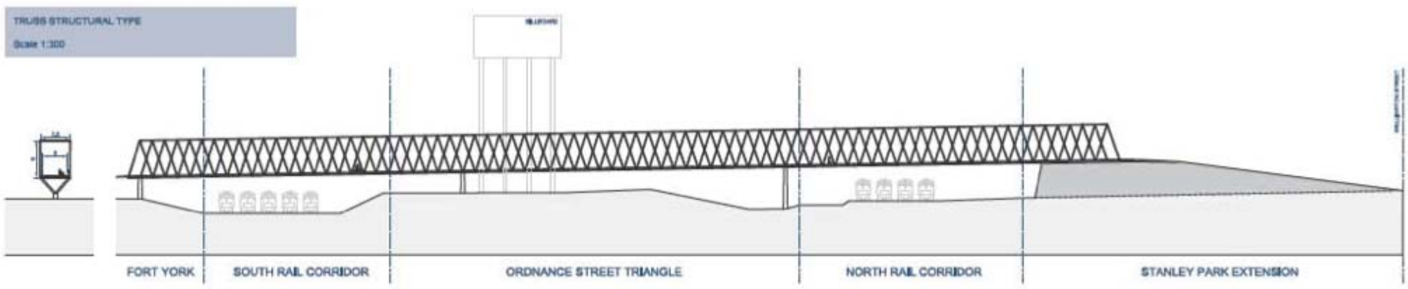
A Bridge in Toronto

On May 18, 2011, Toronto City Council voted not to sign a contract to build the Fort York Pedestrian Bridge.[1] This bridge, shown in Figure 1, was intended to connect three parcels of land currently separated by two railway lines. Due to its proximity to the historically significant Fort York, a high standard of aesthetics was required. The bridge turned out to be just too expensive: the low bid of $22 million was $4 million higher than the amount budgeted. Its cost is indeed high: approximately $16,000 per usable square metre puts it in the same league as some of the most expensive bridges built in recent years.

This option was selected following a study that considered the concept shown in Figure 1, which was taken to final design and put out for bids, and the steel truss span shown in Figure 2. Neither is ideal. The inclined arches, the primary designers of which were architects, create visual impact through an indirect and

Figure 2

Fort York Pedestrian Bridge: Steel Truss Concept (Design: Stantec. Image source: City of Toronto)



extravagant structural system. Whatever aesthetic value they may claim is diminished by the fact that their form is derivative of the large number of recently built inclined arches. (In the Toronto area alone, it would have been the third such bridge.) The positive characteristics we might attribute to the truss (more efficient flow of forces, greater economy) appear unconvincing in the light of its prosaic appearance. It was as if its designers, in this case engineers, did not particularly care about how this bridge would look. Although it is heartening to see a public agency take a stand for fiscal responsibility over an architect's extravagance, it is a mistake to regard this as a victory for engineering. The truss concept produced by the engineers was considered to be so unresponsive to the public's desire for a high standard of visual quality that the city decided to build nothing rather than develop a final design based on the truss.

This bridge in Toronto is one instance of a broader trend in which the engineering profession is increasingly unable to offer much more than tired, simplistic solutions which satisfy code requirements for safety and serviceability, but which often fall far short of satisfying other important requirements. The problem goes beyond the inability to produce works of aesthetic significance, and threatens the credibility of a profession formerly recognized for its unbounded capacity to create value through innovation. The origin of this problem can be found in the way engineers who currently practice the profession were educated.

The Education of Engineers

Although engineering is a practical activity, most engineers in current practice received their formal education from teachers who never practiced the profession themselves. This situation is the outcome of decisions made in the late 1950s and early 1960s to transform schools of engineering into institutions of scientific research. Since then, professors have been hired and promoted almost exclusively on the basis of their ability to fund, perform, and publish their research. Although their duties still include teaching students to practice engineering, whether or not these professors have experience in that very practice, or even an affinity for it, is deemed to be of little or no relevance.

We accept this as perfectly normal, even though we would likely not accept a similar situation in other professions. How would we react, for example, if we were to undergo surgery at the hands of a doctor who had received all of his training from professors who had never performed a single operation? In this regard, engineering stands apart from the other professions.

Some would argue that professors whose primary allegiance is to scientific research are best able to give students a rigorous education in the "basics", which can then be applied to a broad range of practical situations. In fact, what these professors teach to undergraduates is generally limited to methods for calculating forces in structures and for dimensioning the simplest of components.

An understanding of the behaviour of structures is eschewed in favour of a universal ability to calculate using general methods of structural analysis. Questions related to the choice of structural system are usually not discussed at all.

Graduates thus enter the profession not only ill-equipped to do much more than dimension components in standardized systems, but also with the expectation that this activity is the primary extent of their responsibility as engineers. Indeed, they consider the primary measure of their prowess as engineers to be their ability to perform highly detailed analyses of structural systems. This is precisely the type of engineer who, faced with the task of designing a pedestrian bridge, will either defer to an architect or design a prosaic truss, regardless of whether or not the chosen system is the most suitable solution.

This way of educating engineers has been recognized by a growing number of professors as an inadequate preparation for the practice of a creative profession. This has in turn led to a wide range of educational initiatives intended to increase the competency of engineering graduates in design. Here, design is understood in a much broader sense than merely dimensioning components in standardized systems. The resulting transformations to the curriculum have been significant and include new courses for first-year undergraduates in the fundamental principles of design as well as fourth-year "capstone" design projects.

Although the underlying motivation to improve the quality of design practice is certainly commendable, the resulting changes to the curriculum have for the most part been developed and implemented by those same professors of engineering who have never practiced design themselves. Design, however, remains a practical activity. Attempts by those who have not practiced design to specify how it is to be taught therefore warrant a critical look. Recent initiatives to create a more "design friendly" curriculum generally include the following common elements:

1. *The process of design is paramount.* Students are taught to follow a formalized set of steps (sometimes referred to as the "product development process"). This process is independent of any specific engineering discipline. It emphasizes brainstorming, creativity, and methodologies for making decisions on the basis of complex criteria. There is nothing wrong per se with introducing some formal elements on how to approach design. In fact, designers must normally do certain things (e.g. understand the geometric constraints limiting the possible locations of bridge piers) before doing others (e.g. lay out the spans). The design process has, however, taken on a position of importance in the curriculum that is disproportionate to its true significance in practice. In particular, the current approach creates an impression that mastery of this process is really all that is needed for competency in design. This has led to the absence of certain crucial elements of design pedagogy from the curriculum.
2. *The product can be disregarded.* A design process that emphasizes "thinking outside the box" implies that what is inside the box is at best not important and at worst an impediment to the creative process. Design thus becomes an intransitive verb, in the sense that students are taught to "design" rather than to "design a bridge". Although this is a convenient approach to design education when faculty members have never designed bridges themselves, it disregards a primary fact of design practice. Engineers are rarely asked to design a "system to convey pedestrians and vehicles across a valley", which might lend itself to thinking outside the box. Instead, they are asked to design a bridge across a valley, which lends itself to the use of knowledge of other bridges that have crossed similar valleys, i.e., thinking inside the box.
3. *Scientific principles need not be integrated.* A general design process that can be applied to any situation does not require learning specific scientific knowledge. In fact, it is now common to teach the process to first year undergraduates, who have little or no scientific knowledge to apply. This has led to the creation of a "design ghetto", in which there is minimal integration of scientific principles into the teaching of design.

As a result, students do not gain a proper understanding of the role of science in engineering design and are thus not able to exploit its power within the design process.

4. *Drawing is taken as an afterthought.* Although drawing is regarded even by laymen as central to the act of design, it is increasingly difficult to find an engineering curriculum that contains formal instruction in drawing, and practically impossible to find one that teaches students to use drawing as a primary tool in the design process. When it is taught at all, drawing is treated as a way of merely communicating an idea once it has been defined, rather than as a means of generating and validating the idea.
5. *Design is a team sport.* According to the current "process based" model of design education, which favours brainstorming, the more brains that are brought together, the better the ideas that will emerge from the process. Because thinking outside the box is valued, it follows that the greater the diversity of backgrounds, the better the design. The insistence that design projects must be done by teams, not individuals, has become a sacrosanct element of the current orthodoxy of design education, in spite of any compelling justification based in fact, and in spite of the well known layman's understanding of the dubious value of things that are "designed by committee".
6. *Design is everything that needs to be taught but cannot be fit elsewhere into the curriculum.* In most first-year undergraduate design courses, in addition to the design process mentioned previously, we find the following topics: project management, sustainability, scheduling, English composition, oral presentations, and professional ethics. Although a convincing case can be made for including all of these topics in the curriculum, it is a somewhat sad reflection on the value placed on design in the curriculum to see it regarded as a catch-all for topics that, truth be told, have little to do with the essence of design.

The justification of several fundamental aspects of this "new orthodoxy" of design education is thus rather shaky, and it is not at all self-evident that this approach to design education will actually produce better designers than the curriculum that it seeks to replace. An engineering curriculum disconnected from the realities of design practice will have a profound effect on the quality of the works designed by the graduates of this curriculum. Although some engineers have always managed to design works that embody innovations that are truly impressive and inspiring, the average body of engineering work produced in recent years indicates a progressive decrease in the overall ability of the engineering profession to create value through innovative design.

The Decline of Engineering Design

The overpass structures crossing Ontario's Highway 400 provide evidence of this decline. Construction on this freeway, the province's first, began in the late 1940s and proceeded gradually northward from what were previously the outskirts of Toronto. The highway will eventually terminate in Sudbury, some 400 km to the north. The bridges crossing this highway were all built to satisfy similar functional requirements. Traveling north along Highway 400 thus provides the opportunity to view the evolution of bridge technology in Ontario, and hence the level of competency of the province's bridge engineers, from the late 1940s to the present. Two such structures are shown here for comparison. The first, the St. Vincent Street Underpass (Fig. 3), was built in 1966 and the second, the Cranberry Marsh Road Underpass (Fig. 4), was built in 2002. The former is a cast-in-place post-tensioned concrete slab resting on individual cylindrical concrete columns. The latter has a superstructure consisting of precast pre-tensioned concrete I-girders and cast-in-place concrete deck slab, resting on a multiple column concrete bent. The Cranberry Marsh Road bridge is an example of the most common type of structural system currently used for freeway overpasses in Ontario and many other parts of Canada.

An observer would be forgiven for thinking that the St. Vincent Street bridge was the more recent of the two. This mistake originates in our expectation that technology is in a state of constant

Figure 3

St. Vincent Street Underpass, Barrie, Ontario (Design: Ministry of Transportation of Ontario)

Figure 4

Cranberry Marsh Road Underpass, Wahta, Ontario (Design: R.V. Anderson Associates)

progress. For bridges, this trend is associated with increasingly efficient use of materials, which for girder bridges is reflected visually by the superstructure span to depth ratio. For the Cranberry Marsh Road bridge, this ratio is approximately 17:1. The St. Vincent Street bridge, with a span to depth ratio of 35:1, is more than twice as slender. One would be hard pressed to find a constant depth concrete bridge of such slenderness built anywhere in Canada or the US in the past twenty years.

The design of St. Vincent required a greater level of technical competence than Cranberry Marsh. Cranberry Marsh is a standardized design; its dimensions and details were all decided in advance by someone other than the designer of record.[2] Although post-tensioned slabs were in common use in Ontario in the 1960s, the system was never standardized. The design of St. Vincent thus required that primary dimensions and details be determined by the designer, who in turn would have had to understand the behaviour of a relatively complex structural system. That this was done successfully by engineers who did not have digital computers is particularly impressive.

One also gets the impression that the designers at Cranberry Marsh Road did not care about the way their bridge looked. The bridge originates from a standard design, so design decisions had minimal impact on its visual aspect. With St. Vincent, all of the primary factors that contribute to its visual impact—the choice of the cross-section, depth of superstructure, and shape of curve defining the underside of the cross-section—required conscious decisions by the designer. Although we do not know what were the specific factors that drove these decisions, it is a fact that none of these choices resulted directly from a calculation or a standard, i.e., these choices required judgement on the part of the designer. Ontario's Highway 400 bears witness to a decrease in quality in bridge design over the past fifty years. It is easy to blame this decline on public officials who are too conservative or on procurement methods by which designers are selected on the basis of low fee. This would imply, however, that the engineering profession has a strong capacity to create value in the broadest sense that is waiting in the wings to be given a chance to fulfill its destiny. This is inconsistent with the education engineers have received in recent decades. To design works that create value, engineers must be educated accordingly. Such an education must be founded on an understanding of the nature of design as it is practiced at the highest levels, i.e., at its most innovative.

What is Engineering Design?

Practicing designers do not spend time reflecting on the definition of design. They know what it is because that is what they do. Whether or not they can articulate a definition of what they do that can serve as a basis for teaching it to others is really not their concern. If professors of engineering had solid practical backgrounds, there would be little need to spend time defining this activity, because their understanding of design would be reflected in what they taught and how they taught it. It is precisely because universities need to use scientific researchers to teach design that it is of primary importance to define design correctly.

Design is an activity that is undertaken in response to a specific need to create a new useful thing. Its outcome is a description of this thing. The description must be sufficiently complete and detailed to enable the thing to be built without significant further input from the designer.

The following elements of this compact definition warrant further discussion:

1. Design is associated with the production of a *new thing*, i.e., something that differs significantly from what existed previously. The ability to imagine things that did not exist before and to make them real is called *creativity*. By identifying design as a creative activity, we recognize its affinity with other creative activities such as sculpture, poetry, and music.
2. Design is related to the production of *useful things*. Here, a thing is considered to be useful when it directly helps people to accomplish tasks that result in physical, economic, or so-

cial benefits. In this sense, bridges, furniture, and coffee cups are all useful things. Although performing a song and writing a poem are both creative activities, and both can enrich our lives, they do not help people to accomplish specific tasks. This aspect of the definition thus distinguishes design from other creative activities such as the fine arts.

3. Design is undertaken in response to a *specific need*. The implication is that there is an *expectation* that the design will be completed within a specified length of time and the useful thing, when built according to the design, will perform as intended. This distinguishes design from invention, which can occur without specific prior intent (e.g. from serendipitous discoveries) and for which expectations of the time required to produce the idea and its effectiveness are far more relaxed.
4. The outcome of design is not the useful thing itself, but a *description* of the thing. This distinguishes design from crafts such as furniture making and activities such as construction and computer programming, the outcome of which is the useful thing itself. This aspect of the definition is also consistent with the fact that the English word *design* and the French word *dessiner* (to draw) share a common etymology. Indeed, the outcome of the design process is often a set of drawings of the useful thing. We separate design and building to *minimize risk*. People build useful things with the expectation that they will perform their function. Failure to perform as expected can result in unacceptable consequences, including loss of human life and financial loss. Because building generally involves significant amounts of capital as well as significant legal exposure, proceeding to construction in the absence of a reliable assurance that the thing to be built will perform as expected is usually unacceptable. By producing a description of the useful thing before the start of building, however, it is possible to demonstrate on the basis of the description that the useful thing is likely to perform as expected. This demonstration is called *validating* a design.
5. The description must be *buildable*. A set of bridge plans, for example, should be sufficiently complete and detailed to enable a contractor to tender a binding fixed-price offer to build the bridge and then to build it on this basis without significant input from the designer. This distinguishes design from activities such as planning, the outcomes of which are descriptions of useful things at a level of detail that is insufficient for construction. A plan of a new subdivision, for example, might identify the need for a primary school, a storm water drainage system, and a bridge across a river, but the description of these facilities given in the plan would fall short of what would be required for them to be bid and built.

The Design Process

Design is an activity that progresses over time, and thus it is common to speak of a design process. Much has been written about the design process in academic journals in recent years and much attention is also devoted to the design process in the engineering curriculum (Dym et al. provide an extensive bibliography of this activity).[3] It is not by learning and following a specific process that one becomes a competent designer. A proper understanding of the nature of the design process is necessary, however, for those who wish to teach design effectively. For this, we focus on the primary elements of the process that are common in any design setting.

The design process has the following three stages: Definition, Creation, and Refinement.

During the first stage, Definition, the specific functions that the useful thing needs to perform are described. This stage is primarily the responsibility of the entity that will put up the capital for building the useful thing (or that will eventually assume ownership for it). The outcome of this stage is usually a formal set of *design criteria*, which not only define the designer's contractual requirements towards his client, but also constitute the primary basis for subsequent validation of the design. It is therefore not uncommon for the designer to provide input into the production of design criteria, if only to express the client's requirements in terms that can be used as a suitable basis for validating designs.

Figure 5

Royston Road Underpass, Vancouver Island, BC (Design: Paul Gauvreau)

Figure 6

Royston Road Underpass: Alternative span arrangements

The second stage of the process, Creation, can begin immediately after completion of the Definition stage. The Creation and Refinement stages are similar in that they both involve a series of decisions, each of which adds an increment of definition to the description of the useful thing. The outcome of the Refinement stage is the complete, validated, and buildable description of the useful thing.

The demarcation between the Creation and the Refinement stages can best be understood by considering the information content of the individual design decisions. Not all design decisions are equal in this regard. For example, in the design of the bridge shown in Figure 5, Royston Road Underpass, we can compare two specific design decisions.

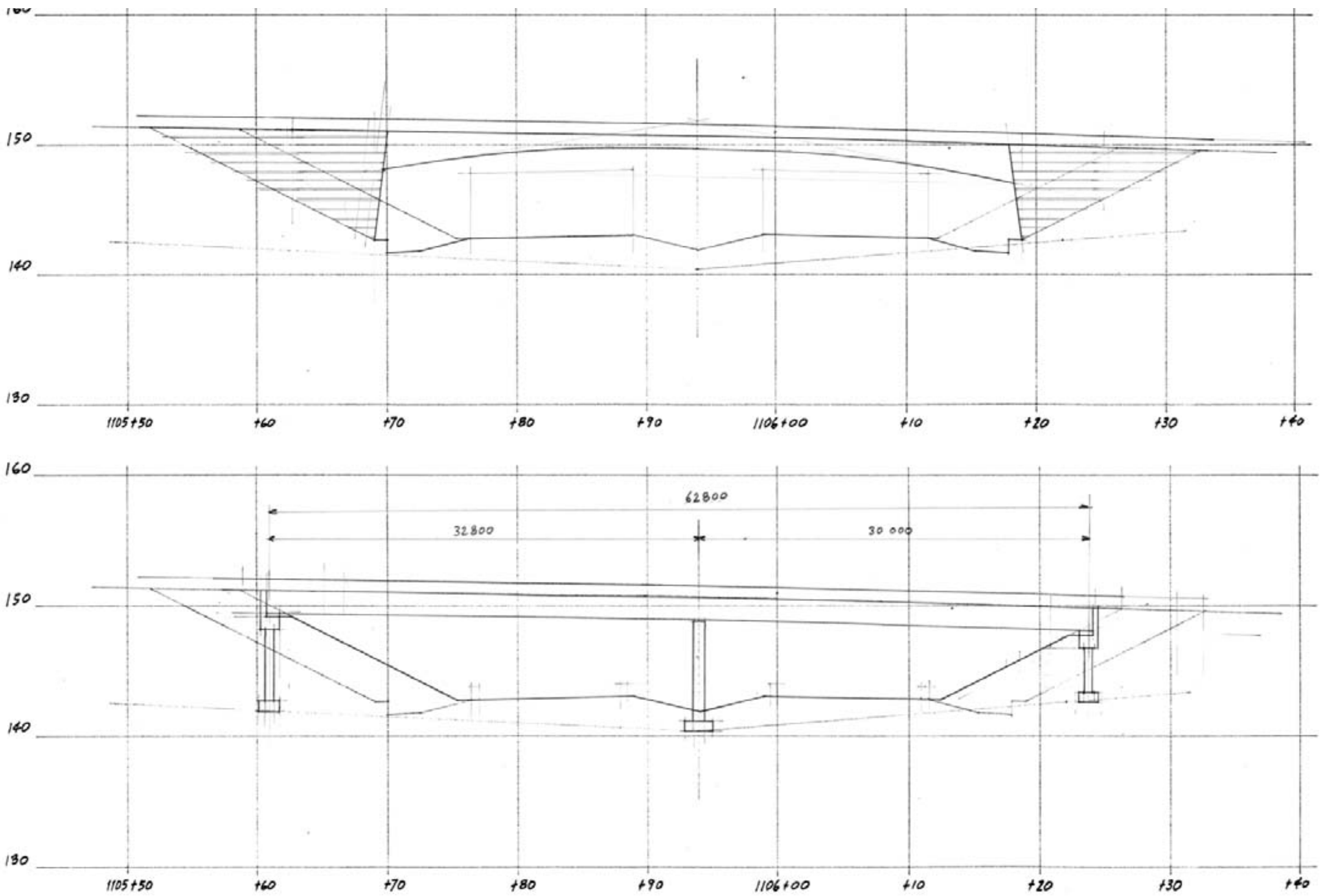
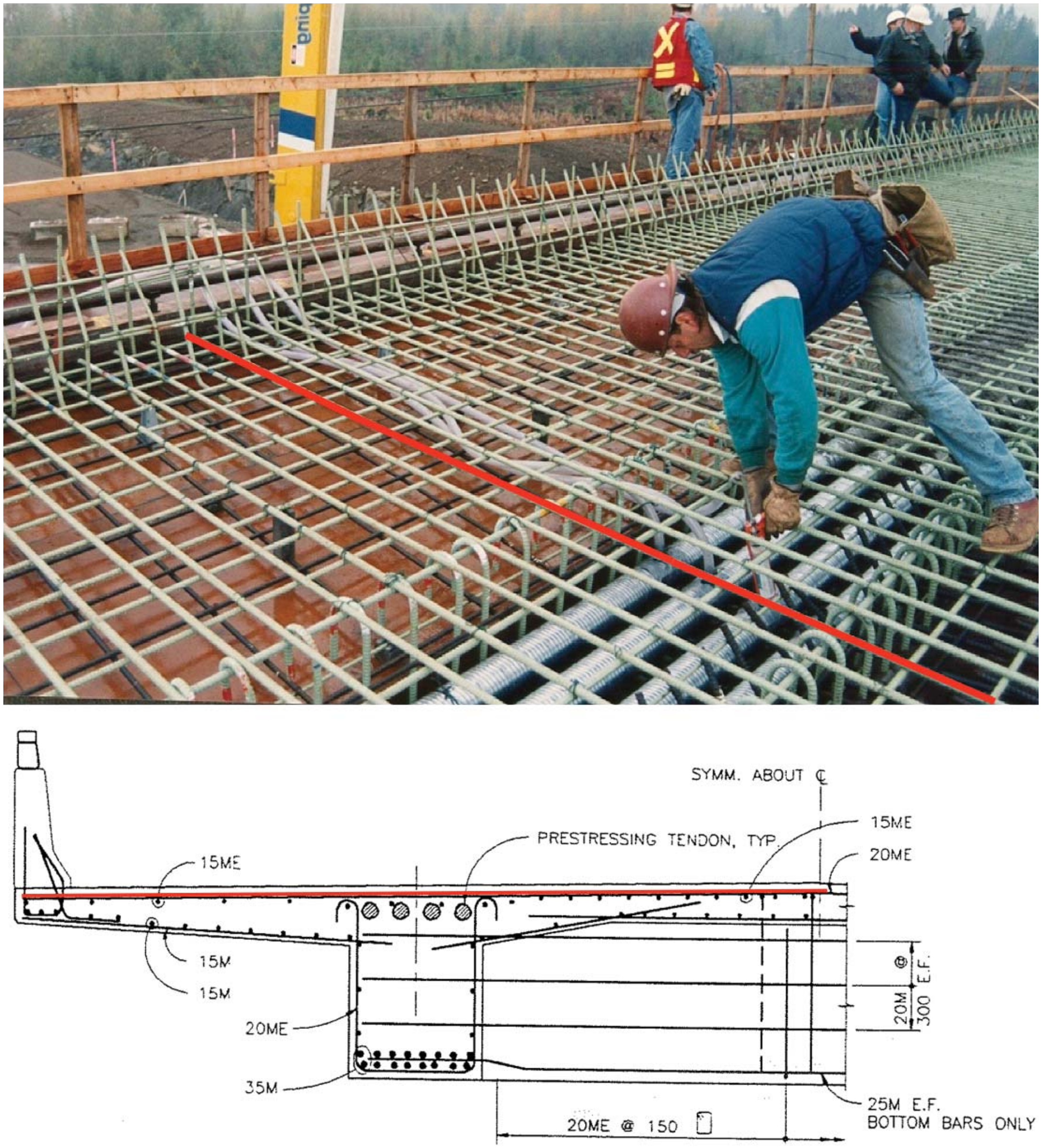


Figure 7

Royston Road Underpass: Deck slab reinforcing steel (Photo source: Kumar Buvunendaran)



The first is the arrangement of spans. This is a bridge that will carry a two-lane local road over a four-lane freeway. A decision needs to be made regarding the arrangement of spans, namely, to design a one-span or a two-span bridge (Fig. 6). The outcome of this single decision has a major impact on the aesthetic qualities, construction cost, traffic safety, and duration of construction of the bridge. The possible outcomes of this decision are immediately recognizable as significantly different in several ways (visual qualities, method of construction, overall structural behaviour). We say that this design decision is associated with a relatively high increment of definition of the final design.

We compare this to the decision of the size of a given reinforcing steel bar, say one of the top transverse bars in the deck slab of the bridge. One of these bars is shown in red in the photo and drawing of Figure 7. Whether these bars are 20 mm diameter or 25 mm diameter affects the ability of the deck slab to carry load, so this decision is important. It will have no effect at all,

Figure 8

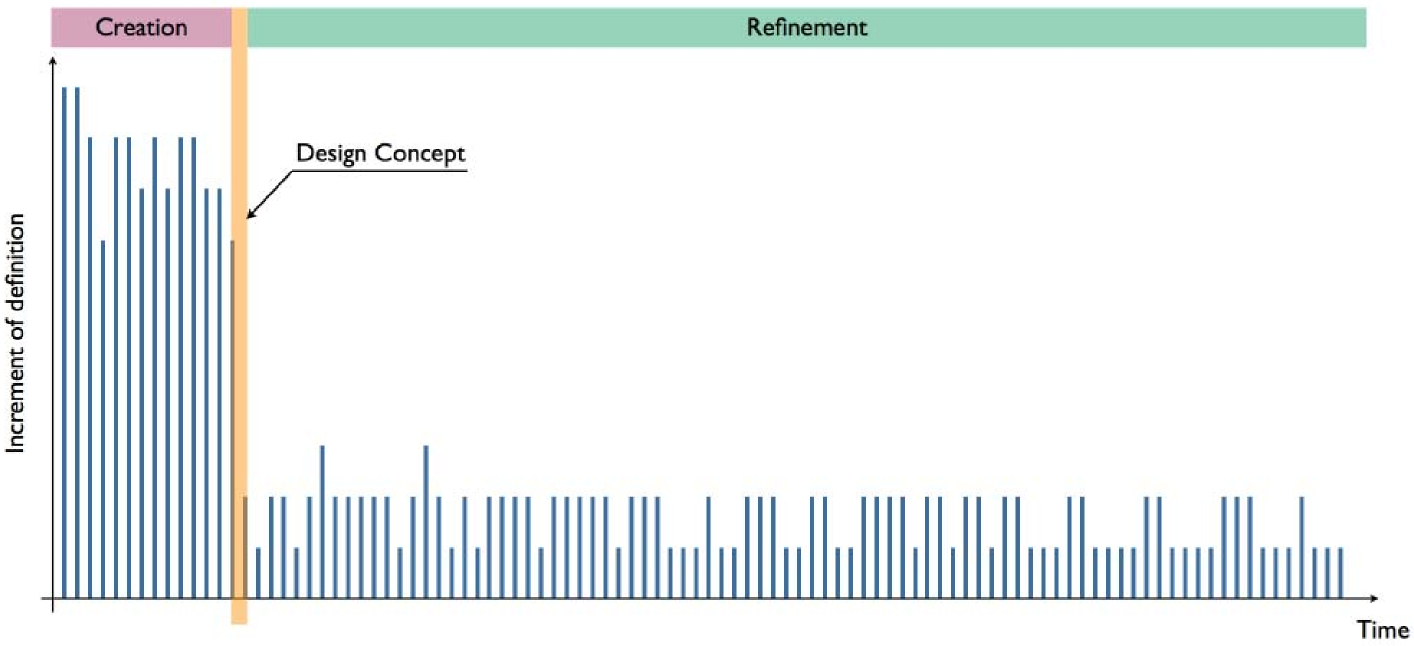
The design process: Increment of definition of design decisions as a function of time

however, on the aesthetic qualities of the bridge, traffic safety, or duration of construction. It will affect construction cost, but this impact will be minimal compared to that of the choice of span arrangement. We therefore say that the dimensioning of this piece of reinforcing steel has a relatively low increment of definition of the final design.

We can plot, schematically, the increment of definition of design decisions as a function of time. This is shown in Figure 8. We observe that the decisions with high increment of definition tend to occur early in the design process, and those with low increment occur later in the process. We also observe that the increment of definition drops rather sharply at some point in the design process. We use this point to define demarcation between the Creation (left of the drop) and Refinement (right of the drop) stages of the design process.

In the Creation stage, designers decide on the primary characteristics of the design. For bridges, this includes arrangement of spans, dimensions of primary structural components, type of foundations, and method of construction. The outcome of this stage is called a design concept, which is an incomplete description of the final product, in the sense that not all components have been dimensioned. The useful thing thus cannot be built on the basis of a design concept alone. It is sufficient, however, to validate many important design requirements. Menn provides further insight into the nature of the design concept as it relates to a specific work of engineering, the Sunniberg Bridge.[4]

In the Refinement stage, designers complete the dimensioning of all structural components and prepare the final, buildable description of the useful thing (plans and specifications). In concrete bridges, the primary activity within this stage is the dimensioning of all reinforcing and prestressing steel.



The intellectual effort that is used in the Creation stage requires creativity, insight, and experience. The work in this stage is best left to mature, fully competent designers. In the Refinement stage, the intellectual effort required is primarily analytical and computational. Generally speaking, these tasks can be performed by younger, less experienced designers.

It was stated previously that designs need to be validated, i.e., it must be demonstrated explicitly that the useful thing that will be built according to the design is capable of satisfying its design criteria. Although this could be done in a separate stage of the process after all decisions have been made, it is usually more efficient to validate individual design decisions or sets of decisions during the course of the process. Criteria regarding speed of construction, for example, can be verified once the primary structural systems and dimensions have been defined. There is no need, for example, to wait until the reinforcing steel has been dimensioned. In some cases, individual design decisions embody an implicit increment of validation. Dimensioning criteria, for example, are generally done in accordance with requirements from design standards. Decisions made according to these criteria will generally satisfy requirements related to safety.

Design and Knowledge

It is fashionable to characterize design as thinking "outside the box", i.e., deliberately throwing away knowledge of previous solutions to similar problems. The underlying assumption is that sticking with the tried and true prevents designers from finding innovative solutions. Although there is some truth to this assumption, it is overly simplistic and inconsistent with the realities of design practice to insist that designers must always be working in this way. Most designers, even those whose work is recognized as being particularly innovative, embrace the body of knowledge of works within their chosen specialty, and can in fact usually be found working "inside the box". A proper understanding of the nature of design thus requires that we understand the role played by knowledge within the design process.

Designers are required not only to deliver solutions that work, but also to deliver them within a prescribed length of time. Designers who use the body of knowledge of relevant completed works (referred to here as reference works) have access to a set of generally suitable ideas that have been effectively pre-validated. Simply put, if it has worked in the past, it can work again. The use of reference works thus offers designers a means of minimizing the time and effort required to produce a valid design.

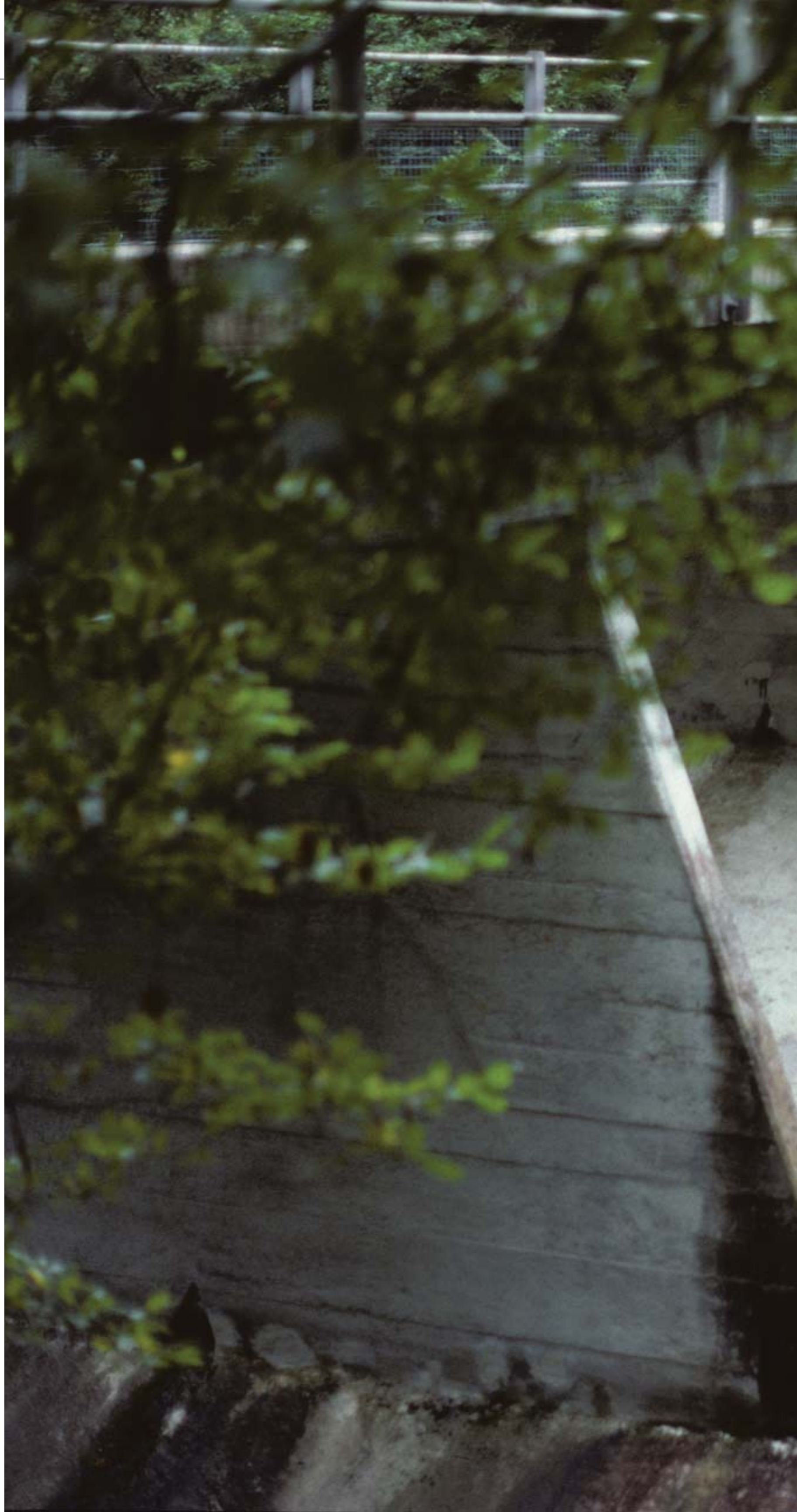
Obviously, by choosing to re-use previous ideas, designers effectively preclude the creation of new ones. It is therefore important to understand the relationship between knowledge and innovation in the design process. We can characterize the innovativeness of a given design by the extent to which it departs from the body of reference works that was available at the time of its creation. Robert Maillart's Schwandbach Bridge (Fig. 9), for example, can be regarded as a highly innovative design because its thin concrete arch supporting a curved deck has no antecedents.[5]

Innovation in design is not an end in itself. Because design deals with useful things, a departure from precedent merely for the sake of originality is generally not highly regarded. Instead, designers seek new ideas as a means of solving problems that have not been solved before, or of delivering greater value relative to previous solutions to similar problems. The Schwandbach Bridge's thin arch supporting a curved roadway created value by lowering construction cost relative to other possible solutions and by creating new opportunities for aesthetic expression.

Designs can also be good without being highly innovative. All of the primary features of the St. Vincent Street Underpass (Fig. 3) have antecedents. This is not the first post-tensioned slab bridge to be built, nor was it the first to be made so slender. It is, however, a bridge that was built at an acceptable cost, has performed well for almost fifty years, and which conveys a visual impression of simplicity and elegance that is superior to many overpass structures.

Figure 9

Schwandbach Bridge, Switzerland (Design Robert Maillart)



Because innovation involves moving away from the relevant body of knowledge of reference works, innovative ideas do not come pre-validated but rather must undergo an explicit validation. This can be a significant challenge to designers and can present the risk that it will not be possible to validate a given new idea within the time available for the design.

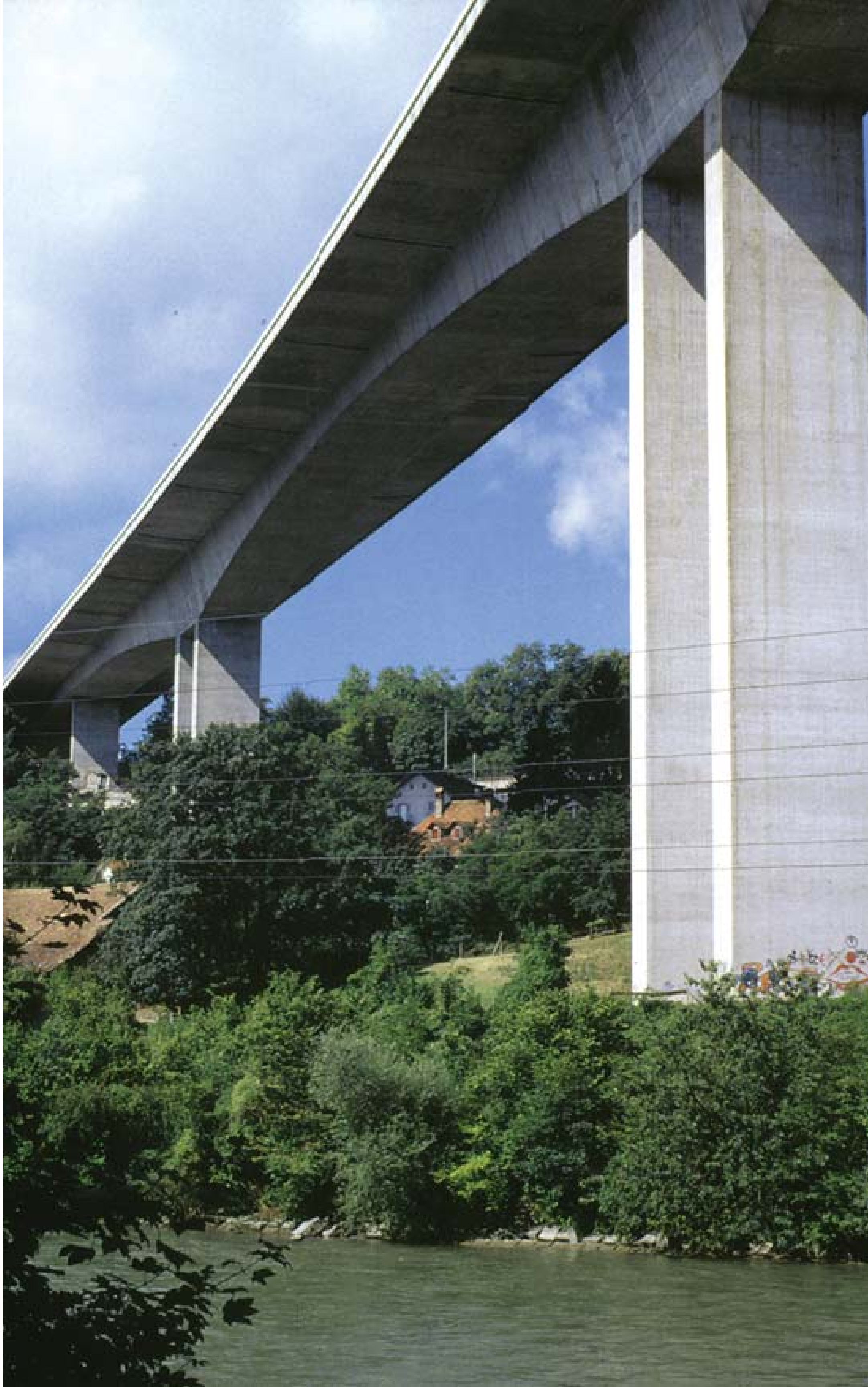
We observe that mediocre designers deal with this challenge by simply avoiding innovation altogether. They make simplistic use of a relatively narrow body of knowledge, essentially copying previous designs. They can deliver designs consistently and on time because they have eliminated as much as possible the risk associated with the validation of new ideas. The outcome of their design process is a product that nominally satisfies the applicable design requirements (safety and serviceability) but which often falls short of being the best solution with regard to more complex requirements such as cost, impact of construction, or aesthetic significance. The Cranberry Marsh Road Bridge (Fig. 4) is the outcome of such a process.

Good designers draw on a much broader body of knowledge and use it with a greater degree of sophistication. Although antecedents are recognizable in their work, it is clear that their designs are not mere copies of another reference. And although these designs would generally not be called innovative, they are the result of an adaptation and transformation of reference works that required significant creative thought. Compared to the work of mediocre designers, these designs tend to provide better solutions to the more complex design criteria such as cost, impact of construction, and aesthetic significance. The Royston Road Underpass (Fig. 5) is the outcome of such a process.

The work of the best designers usually embodies clearly recognizable innovations. These innovations create significant value over and above the current state of the art,

Figure 10

Felsenau Bridge, Switzerland (Design and image source: Christian Menn)



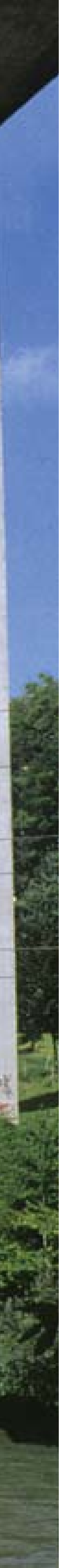
and some of them establish new directions for designers for many years to come. In spite of this, however, it is rare for even the most innovative designs to have no antecedents in the previous body of work. Christian Menn's Felsenau Bridge (Fig. 10), for example, embodies several significant innovations including 7.5 m wide, extraordinarily slender deck slab cantilevers. Yet this was by no means the first single-cell box girder to be built by the cantilever method, nor was it the longest spanning structure of this type. Even the most innovative designers have intimate knowledge of relevant reference works and consistently apply this knowledge to their design practice.

Engineering Design

Everything that has been said thus far in this article about design generally applies to any creative activity that has as its outcome the buildable description of a useful thing. We now need to consider what makes design as practiced by engineers different from design as it is practiced in other disciplines.

Engineering design is a subset of the broader activity of design as defined here. It is distinguished from other types of design in that it *uses the principles of science as a primary enabler of innovation*.

We have associated innovation with the extent to which a design departs from previous solutions to similar problems. By



working with concepts that remain close to the body of knowledge of prior solutions, much of the validation at the concept stage can be done by reference. Difficulties arise when we need to validate concepts that depart substantially from past practice. For example, knowing that a given structural system can be used to build spans of 100 m may be a sufficient basis for validating a concept that uses a similar system to span 110 m, but is probably insufficient for validating that system to span 200 m. A reliable basis for validating concepts that depart significantly from past practice is thus required.

The power of science as a tool for design lies in its ability to predict the response of complex physical systems to specific actions. This allows designers to demonstrate, while the useful thing is still "on paper", that their idea will indeed perform as intended. For the case considered above, if we understood Newton's laws and the stress-strain relationships of the materials we proposed to use, we could create a mathematical model of the proposed structural system with the 200 m span, calculate the forces that must exist within the structure to equilibrate the given loads, and then demonstrate that the materials to be used are sufficiently strong to resist these forces. On this basis, we could validate that the proposed concept was capable of withstanding the given loads without collapse.

We can describe the increase in span from 100 m of the previously completed work to 200 m of the proposed concept as an innovation. The principles of science can be regarded as the primary enabler of this innovation, since it was by using these principles to demonstrate that capacity was greater than demand for a given loading that we were able to conclude that the concept would be capable of carrying the given loads.

The use of science as a means of validating new ideas is particularly important when the consequences of invalid concepts may be severe. This explains why engineers assume leadership of the design of systems that involve risk related to human life or financial resources, since their command of the principles of science gives them the means of validating these designs before they are built. It is emphasized that the role of science in engineering is primarily to validate ideas that have been created by other means. Although designers can sometimes derive inspiration from an understanding of how forces flow efficiently in a given structural system, such a use of scientific principles is predicated on the prior choice of a system, which is a design decision that is generally made on a different basis. Scientific principles on their own are rarely the source of design ideas.

Likewise, neither the use of advanced scientific principles nor the complexity of the analysis is a measure of the quality of the design. This proposition is illustrated by Figure 11, which shows a rendering of a suspension bridge that is curved in plan. The challenge is to determine the geometry of the main cables and suspenders such that the entire system is in equilibrium under dead load. This is a difficult problem to solve using general structural analysis software packages. These tools can calculate forces due to loads in structures of a given geometry, but are poorly suited to calculate the geometry that establishes equilibrium in flexible structures. The method used in this case was a simple application of the method of graphic statics. A simple CAD package was used to draw the necessary lines in three dimensions. The scientific principles on which this calculation was based can be understood by any first-year undergraduate. A more detailed account of the use of simple scientific principles to validate a complex innovative structural system is presented for the Sunniberg Bridge by Menn.[6]

The use of the principles of science as a means of validating new ideas is the only significant characteristic that distinguishes engineering design from the broader activity of design. Engineering design thus shares much in common with design in other disciplines and indeed with other creative activities. This affinity can and should inform the development of an effective curriculum for engineering design education.

Figure 11

Curved suspension bridge (Design Paul Gauvreau) with corresponding three-dimensional force diagrams (magnitude and direction plan): Each triangle represents the equilibrium of three intersecting forces in the structure

Principles of Design Education

Given the nature of engineering design described in the previous section, one can define a set of principles to guide the development of an effective design-directed engineering curriculum.

General Principles

1. The primary elements of design education are *knowledge, skills, and values*.

Designers use *knowledge* of existing completed works of engineering that solve similar problems as starting points for the creative process and to validate these ideas by reference. This enables designers to proceed quickly and with confidence to valid solutions. Without this knowledge, it would be necessary to re-invent the wheel on every project and to engage in a lengthy and possibly inconclusive exercise in validation. The challenge is to use knowledge of prior works without unduly limiting innovation.

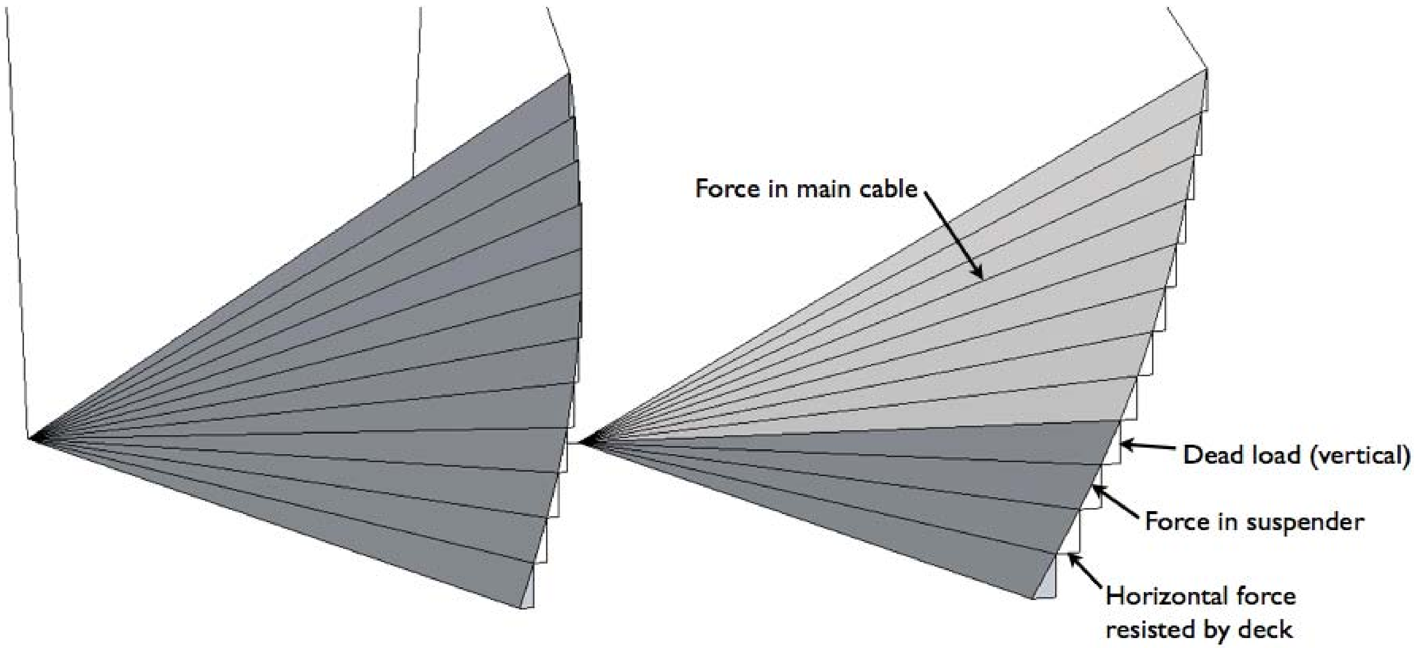
The ability to make good design decisions is referred to as *skill*. This involves both the ability to imagine ideas and bring them

into reality, as well as the capacity to validate these ideas reliably and efficiently. Designers make ideas real by drawing. Engineers validate ideas by drawing and through the use of scientific principles.

Design is a series of choices made from among several alternatives. Each of these decisions requires a basis for determining which of the alternatives is the right choice. The term *values* is used to denote this basis. Values include conventional consideration of allowable stresses and material quantities, as well as ways of assessing ease of construction, durability, and aesthetic significance of designs.

2. The focus of design education should be on the development of valid design concepts.

Most of the conventional engineering curriculum is directed towards activities that take place in the Refinement stage of the design process, i.e., dimensioning components to satisfy requirements related to strength and serviceability. The greatest opportunities available to designers for creating value, however, reside in the Creation stage. As discussed previously, although the di-



mensioning of an individual reinforcing steel bar is important, it has no impact on many important elements that define the overall quality of the project. Good designs come from good concepts. If the concept is wrong, no amount of refinement will make it right. If we want to educate leading designers, then we need to concentrate on the concept.

3. The development of an engineering design curriculum should be informed by approaches to teaching in other creative disciplines.

Engineering design is a creative activity and thus holds much in common with other creative activities. Within these disciplines, pedagogies have been developed that have been validated by the test of time. Many elements of these methods of teaching are applicable to the teaching of engineering design and should be given serious consideration. Conversely, approaches to engineering design education that have no analog in other creative activities should be regarded with a healthy dose of skepticism.

The following sections put forth principles relating to the three main elements of design education (knowledge, skills, and values).

Knowledge

1. Teach design within a discipline.

If you want to design bridges, you should first learn about bridges. This is consistent with the pedagogy of every other creative discipline. Aspiring authors read novels and future architects sketch buildings. The notion of a "generic designer" who, merely having mastered a design process, can create value on any type of design project is a myth. Without a relevant body of knowledge, design will proceed with minimal efficiency and dubious odds for a successful outcome.

2. Select knowledge carefully.

There is little value in teaching students bad or mediocre works of engineering. This is consistent with other creative disciplines, which teach only the great works. Teaching the best works gives students insight into design as it is practiced at the highest level. Even if students never design works of comparable brilliance, their understanding of the masterpieces will inevitably inspire them and inform their approach to the design of everyday projects. It is not necessary to teach only modern works in structural engineering, since most of the structural systems used by the great designers of the nineteenth and twentieth centuries are still current and the materials they used are similar to those used today. Reference works should not be chosen on the basis of popularity, which is often unrelated to quality.

There is little benefit in focusing on the minutiae of stress calculations and other esoteric points of structural analysis, unless they are crucial for understanding important design decisions. Rather, students should be given an understanding of how references "work". This normally includes a clear visualization of the primary load paths, identification and explanation of the most important details, and a description of the method of construction. Upon completion of the study of a given reference work, students should not only be inspired by the structure, they should have the knowledge necessary to produce a design concept for a similar structure.

3. Seek out every opportunity to convey elements of the body of knowledge of completed works.

The importance of teaching reference works of engineering should be acknowledged by the creation of at least one separate course devoted to this topic. This course should not be taught until students have had sufficient elements of the fundamentals of engineering, since these are the principles that will be used to understand the flow of forces and to explain many of the important design decisions.

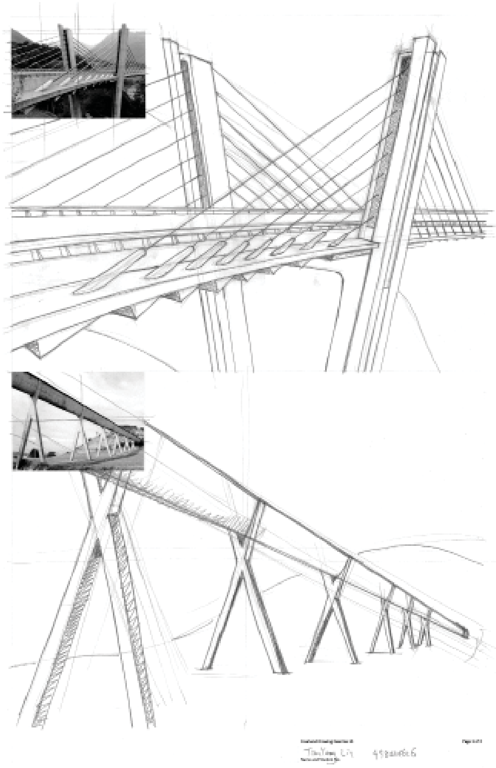


Figure 12

Freehand sketching exercise based on Sunniberg Bridge and Alloz Aqueduct

Other opportunities exist, however, for teaching important elements of this body of knowledge. Reference works can be used as vehicles for teaching just about any topic in the conventional curriculum, including methods of structural analysis and the dimensioning of concrete and steel structures. As a minimum: (1) dimensioned drawings are required, not merely photographs, (2) the structure should be identified with regard to designer, time, and place, (3) it should be described as a whole, if only briefly, and (4) the primary design decisions that contribute to its significance should be identified. The structure can then be used as a basis for examples to illustrate specific topics. Figure 12 shows how a classroom exercise in freehand sketching from photographs can be used as a vehicle for learning about Menn's Sunniberg Bridge and Torroja's Alloz Aqueduct.

Design project courses should be devoted to designing rather than to lectures or other passive activities. If students have not had prior opportunities to learn reference works, however, the design experience will largely be wasted, since they will not have the means to develop and validate design concepts quickly and efficiently. In such cases, it is advisable to undertake a critical study of a small number of reference works before actual design work begins. Such work should be done by independent study rather than by lecture to maintain the active learning mode. Such an exercise will always be justified by the quality of the designs it makes possible.

4. Give students compiled knowledge of many similar works.

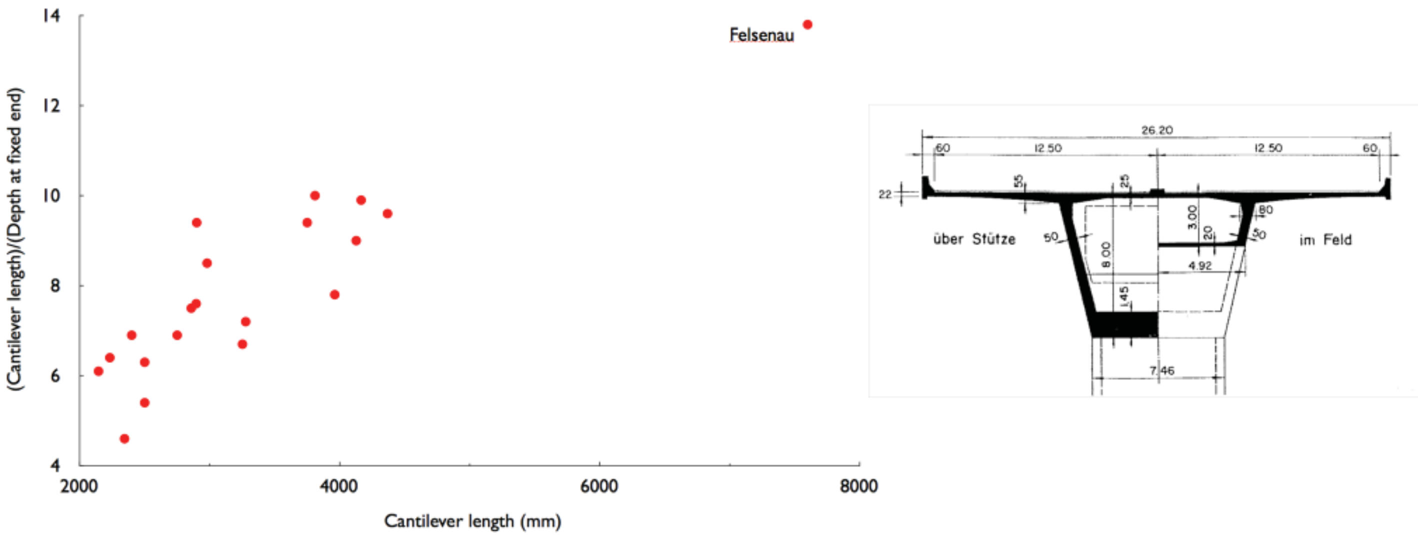
Detailed knowledge of individual reference works gives students starting points for designs that can be validated quickly and efficiently. This generally requires, however, that the references be adapted to satisfy requirements and constraints specific to the given project. This effort can be assisted by knowledge of how the proposed design and the given reference fit into a broader set of similar works.

Figure 13, for example, plots the ratio of deck slab cantilever length to depth at the fixed end as a function of cantilever length for a set of twenty single-cell concrete box girder bridges. The outlying point represents the Felsenau Bridge (Fig. 10). If a student used Felsenau as their reference, the diagram would alert them to the fact that this bridge has exceptionally slender deck slab cantilevers. Validating a deck slab with cantilevers even more slender than this is likely to require considerable effort and may not be successful. On the other hand, decreasing slenderness to move the design closer to the larger cloud of points can likely be accomplished without problem, at least with regard to the transverse behaviour of the deck slab.

This type of diagram improves on the span to depth ratios commonly used by designers because they are better documented (each point is associated with a real structure for which drawings are available) and they give designers an indication of the effort that will be required to validate a given design that is not in perfect agreement with the given ratio.

Figure 13

Span to depth ratio of deck slab cantilevers of single-cell box girder bridges (left), Felsenau cross-section (right).



One of the best compilations of knowledge in bridge design is Christian Menn's study of the construction cost of nineteen prestressed concrete bridges built in Switzerland in the 1950s, 60s, and 70s.[7] A broad range of bridge types was considered. In this study, Menn expressed the cost of specific components such as superstructure concrete, substructure concrete, and prestressing steel, as percentages of total construction cost. (In the originally published version of this study, scaled elevation and cross-section drawings were also provided for each bridge.[8]) This simple study remains one of the only reliable sources of general guidance to designers regarding the construction cost of prestressed concrete bridges.

5. Do not undertake design projects in the absence of a relevant body of knowledge

Although design projects for first year undergraduate students are currently the norm in Canada, the timing makes it practically impossible to have students use a relevant body of knowledge. As a result, the projects have little to do with engineering. These courses thus have negligible impact on the performance of upper year students in real design projects and on future engineering practice.

Skills

The primary skills that need to be addressed in engineering design education are drawing and the use of the principles of science.

1. Provide formal instruction in drawing.

Drawing is too important a skill to be left to happenstance, especially since most students have had little or no formal instruction in drawing prior to their arrival at university. If drawing is not taught formally, then not only will students struggle in their design projects, but they will believe that drawing is not important for engineers.

Engineers need to know how to draw freehand, by hand with instruments, and by computer. Notwithstanding the importance of computers in the modern design environment, drawing by hand provides the most direct link between the human mind and the paper, i.e., the most direct path linking imagination and reality. Any course in drawing should therefore include a significant component of freehand drawing.

2. Teach drawing not just as a means of presenting ideas but as a tool for design.

Although the role of drawing as a means of formally presenting a design to clients or collaborators is important, drawing also plays a crucial role as a tool for designers themselves. Drawing is the means by which ideas are brought into reality. This application of drawing within the design process must also be mastered.

There exists a strong affinity between the drawing process and the design process. As shown in Figure 8, an efficient design process is one in which the decisions that contribute the greatest increments of definition are made first. This is exactly the way drawings are produced, i.e., by placing lines on the page such that each line contributes the maximum increment of definition of the final picture. When students learn to draw, therefore, they are implicitly learning an effective design process. The proper way to draw is the proper way to design.

Figure 14 illustrates this proposition. The bridge shown in the photo is to be sketched freehand using only fifteen lines. As can be seen in the lower left-hand sketch, it is possible to convey a convincing impression of the bridge when these lines have been properly chosen, i.e., by drawing the lines that convey the greatest increments of definition. The process involves the mind as well as the eyes, since it is necessary first to understand the formal arrangement of components before drawing them. On the other hand, as shown in the lower right-hand sketch, it is possible to use fifteen lines to create a properly proportioned, correct drawing that conveys very little of the overall characteristics of the object to be drawn. This is because the lines chosen convey relatively low increments of definition. The situation is identical to the situation discussed previously for the design process and illustrated by Figures 6, 7, and 8.

Another affinity between drawing and design is the notion of incremental validation and correction. Producing a drawing is a process that involves adding lines to the paper, comparing these lines to the visible reality and, if necessary, correcting the lines. Analogously, the designer of a bridge will lay out the spans early on, and then, on the basis of this simple layout, assess the suitability of this arrangement and make a correction if required. This process of continual monitoring and correction is often at odds with students' expectations. Presenting it first within the context of drawing can make it easier to embrace in design.

Drawing is the primary means of validating requirements and constraints that can be defined geometrically. There is no better way to validate required minimum clearance under a bridge, conflicts with foundations and underground utilities, areas restricted for environmental reasons, as well as all types of conditions related to accommodating post-tensioning hardware and reinforcing steel inside specific concrete dimensions than by drawing to scale.

3. Make visual comparisons when working with reference structures in the design process.

The use of reference works in the design process can be greatly enhanced by a linked graphical presentation of concept and reference. This is illustrated in Figure 15. The task is to design a bridge to carry two lanes of traffic over a valley. The designer has chosen Christian Menn's Bridge over the Rhine at Reichenau as a reference. The chosen views of the reference, longitudinal section and cross-section, correspond exactly to views of the concept, and all corresponding views have been drawn to the same scale. The corresponding views of concept and reference have been properly linked by matching centrelines and midspan axes.

Figure 14
Information content in the drawing process

This presentation enables the designer to validate the choice of reference by means of a visual comparison of primary geometrical design requirements. It is evident that both bridges cross valleys of comparable length and depth. Both carry roadways of comparable width. Had the images not been properly linked, this inference would have been more difficult. Had identical views of concept and reference drawn to the same scale not been provided, this inference would have been impossible.

This presentation also enables the designer to use the reference as a basis for validating the concept. From the drawing, we see that the arch span of the reference is longer than that of the concept and both arches have similar rises from springing lines to crown. On this basis, it could be concluded that the arch proposed for the concept is likely to be feasible. On the other hand, we see that the concept uses a different girder cross-section than the reference. This should inform the designer that the choice of cross-section may warrant closer attention to validate its feasibility. This type of drawing thus provides a visual means to validate design decisions directly as well as indications of what aspects of the concept require special attention for validation.

4. Insist on a high standard of drawing in all courses.

There are plenty of opportunities to draw in all engineering courses. Models of structural systems, bending moment diagrams,

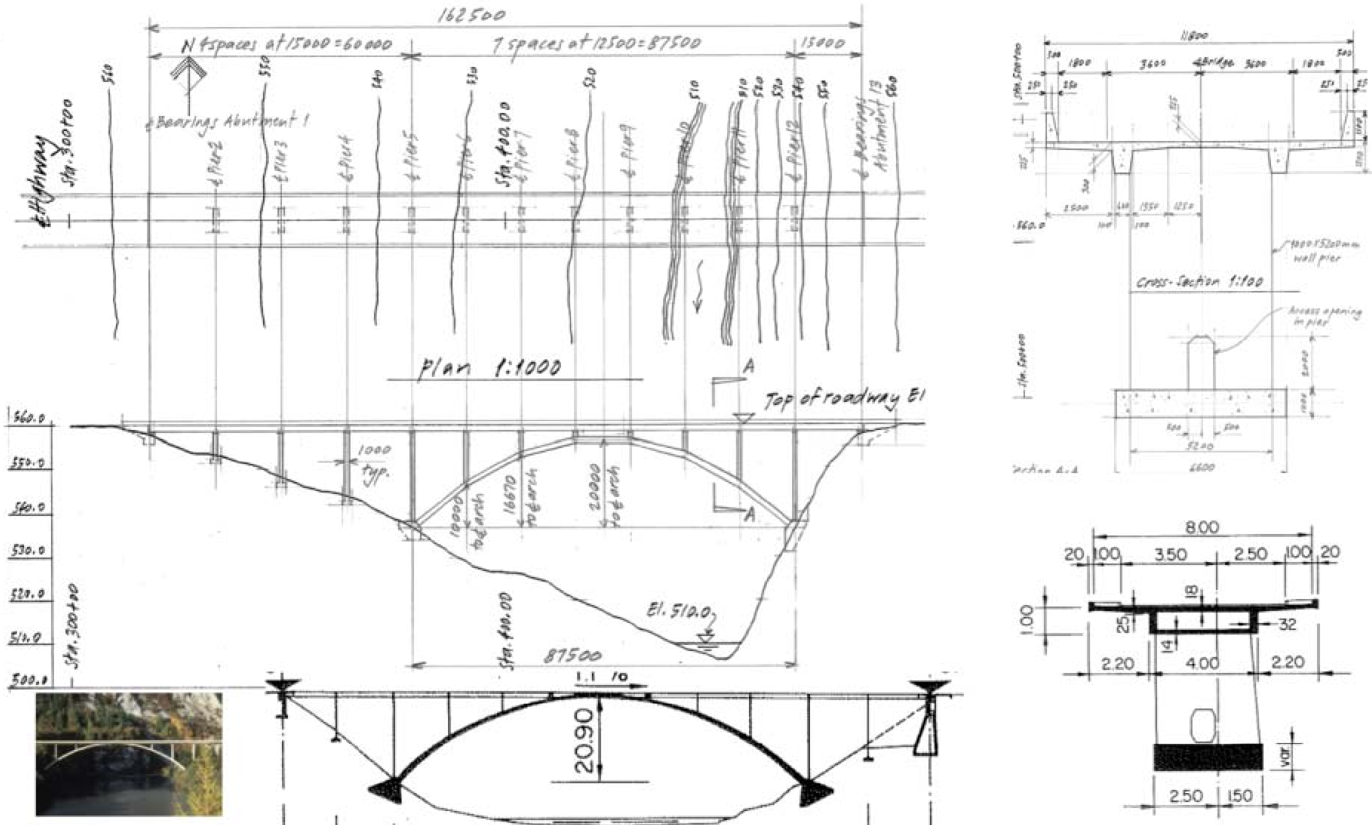
Figure 15

Linked images of design concept and reference work

graphs of quantitative information, all need to be drawn. All too often, shoddy drawings are accepted provided the associated numerical values are correct. This is a lost opportunity not only for students to practice drawing skills, but also to integrate drawing into every aspect of their activity as engineers. The more our students draw, the better they will draw, and the more they will come to accept that drawing is an important part of what engineers do.

5. When teaching scientific principles, always identify their role as enablers of innovation.

Scientific principles are often taught in a vacuum. Courses on structural analysis, for example, give students the impression that calculation of a bending moment diagram is an end in itself, rather than the means to an end. Courses in concrete structures give students the impression that the dimensions of concrete structures materialize out of thin air and all that is required is to dimension reinforcing steel. Teaching in this way makes no connection between a given principle and its role as an enabler of innovation. This needs to be taught consciously and formally.
It is not enough merely to present more practical examples of how



Bridge over the Rhine at Reichenau, Switzerland
Designer: Christian Menn

to calculate. Rather, instructors should work with specific innovations obtained from real works of engineering. There is no shortage of such examples. Maillart's deck-stiffened arches,[9] Maillart's three-hinged arches,[10] and the slender deck slab cantilevers of Menn's Felsenau Bridge[11] are all excellent examples.

In this age of ubiquitous computing, it is tempting to regard the task of validation as one that can be accomplished in the same way for all cases, namely, using a software package that has implemented the general methods of structural analysis. This perspective does not recognize the role played by insight in the validation process. Although developing a specific, simple, and rational method for validation requires initial effort, it not only leads to significant reductions in the total effort required, but can also yield a deeper, more general understanding of the most important aspects of structural behaviour. The use of three-dimensional graphic statics discussed previously is an example of how one simple method can be used to determine a suitable structural geometry, calculate forces in members, and visualize the overall flow of forces. Truss models for stress fields in concrete structures are another method that offers similar insight, simplicity, and accuracy. It is unfortunate that graphic statics has been abandoned in just about every university curriculum in favour of algebraic methods of structural analysis, and that truss models, if taught at all, are covered only at the graduate level.

Values

Designers need a suitable basis for deciding whether or not the design decisions they make are correct. In the conventional engineering curriculum, design decisions are limited to the Refinement stage of the design process, and thus pertain mainly to the dimensioning of structural components to ensure safety and serviceability. The basis for these decisions is to compare demand (stress due to the action under consideration) and capacity (allowable stress of the material). These calculations are straightforward and require no further coverage in the curriculum.
Greater challenges arise with regard to decisions made in the Creation stage of the design process. These decisions often involve requirements that are intrinsically complex and contradictory and cannot realistically be quantified. The new "design friendly" curriculum proposes methodologies for dealing with these situations that usually involve quantifying the unquantifiable. If compliance with design criteria can be expressed in terms of numbers, then it follows that the solution with the highest score is the best. Although this simplistic approach is unconvincing, it appeals to professors because it is easy to apply in student design projects.

It is more realistic to accept that the situation is complex and criteria are contradictory, and to make design decisions on the basis of values. This approach recognizes that part of a designer's competency must reside in his ability to deal effectively with complexity rather than to simplify it out of existence. Although working with values appears incompatible with the quantitative emphasis of the current curriculum, students are generally willing to embrace this approach provided they are given suitable guidance.

1. Engage in critical study of reference works.

Students need to study reference works not just to acquire factual knowledge, but also to acquire a critical perspective. Students should thus be challenged to present their views on whether or not a given work is good, and introduced to a suitable framework for justifying these views. This type of activity gives students a sense of the importance of values in design as well as experience in applying these values to real works of engineering. When good reference works are selected for critical study, students gain important insight into what exactly are the hallmarks of quality in engineering design. Learning to look at works critically is consistent with the pedagogy of all creative disciplines.

Bridges lend themselves well to critical study because their visible form is such an important part of their essence. It is easy to get students to voice their opinions on how a given bridge looks. From this starting point, students can be challenged to describe the relation between the way the bridge looks and the way it carries load, which is a simple but effective framework for assessing design decisions related to aesthetics. The study can then be expanded to identify important design decisions related to a broader set of criteria, such as cost and impact of construction.

2. As a teacher, develop values of your own.

There is never a single best answer to questions that deal with complex and contradictory design requirements, but there are good answers and bad answers. Teachers must be able to articulate a clear and informed assessment of the quality of design decisions in their critiques of both reference works and student design projects. For this to be possible, teachers must have a well developed set of values of their own.

This is consistent with the pedagogy of other creative activities, in which much of the teaching and learning occurs through the teacher's critique of the student's work and the student's response to this critique. Teachers who have no basis to critique other than the precision of calculations will be of little value when challenged to assess whether not a design has satisfied requirements related to construction cost, impact of construction, and aesthetics. In the current "design friendly" pedagogy, the inability or unwillingness of professors to embrace the complexity and contradiction inherent in important design decisions has been dealt with either by defining design projects that have overly simplistic requirements (such as the "useless widget" build-a-robot projects), by attempts to quantify the unquantifiable, or by "peer critique", in which responsibility for assessing the quality of design work is downloaded onto the students themselves. None of these approaches is acceptable.

3. Challenge students to develop and apply their own values.

We must accept that, when teachers critique student work on the basis of their own well developed set of values, students will tend to develop values similar to their teachers. This must not be viewed as an unfair restriction of students' creative freedom, but rather as a necessary step in the process by which students mature as designers. It is by working initially within a value system provided by their teachers that students can develop their own set of values.

Values belong to individuals, not teams, and each individual student must be given opportunities to develop their own values. This proposition is of course in conflict with the current orthodoxy of engineering design education, which holds that all design work should be done in teams. This attitude continues to prevail in schools of engineering, in spite of its complete lack of consistency with the pedagogy of any other creative endeavour and the fact that none of the great engineering designers of the past was a "team player".[12]

The human creative spirit is motivated by the exquisite pleasure that results from bringing forth into reality something good that originated in one's imagination. This is a selfish pleasure, for it is when the individual defines what is truly good, when the individual invests the creative effort and takes all associated risks, and when there is no one to please but oneself, that the pleasure is the greatest. When we insist that all designs must be done by groups, we deprive individuals of the opportunity to savour this rare pleasure, and hence rob them of motivation to do their best work. It is for this reason that the best works of engineering design, and of any creative endeavour for that matter, have always been the fruit of an individual's imagination.

If it is created by an individual, then there is a simple chain of responsibility for the design. When it is created by a team, there is only corporate responsibility. Billington linked the lack of individual accountability resulting from design by "anonymous teams" to deficiencies in the quality of recently built bridges.[13]

The task of educators in any creative field is to provide a suitable structure to guide the thinking of students in the early years while at the same time recognizing and rewarding good thinking that departs from this structure. In this age of self-esteem, it is particularly important for teachers to maintain a suitable degree of rigour and not to praise thinking that is merely original, but rather only thinking that is good. Here, there is much to learn from our colleagues in architecture, who have long recognized the value of sharp critique of student work as a primary pedagogical method.

How to Implement

The principles outlined in the previous section can be used as the basis for a curriculum that is truly effective in educating competent design engineers. These elements of design pedagogy can for the most part be implemented without additional resources. For example, resources currently invested in design courses for first-year undergraduates, which are of minimal effectiveness, could be shifted to courses devoted to acquiring knowledge and critical study of important reference works. It is also possible to give just about every traditional engineering course a much stronger design direction through the suitable use of reference works of engineering as vehicles for teaching. The additional time required to present these works is usually compensated by a much higher level of motivation among the students.

The primary difficulty, however, remains the faculty. Implementing the vision of design education outlined in this article requires professors who take their responsibility to educate designers seriously, who have acquired a suitable body of knowledge of completed works within their discipline, who have achieved a level of proficiency in the skills required of designers, and who have developed a mature set of values. Engineers who have practiced design at a high level for many years will have acquired all of these qualities out of necessity. It is unlikely however that universities, at least in the short term, will step away from the current practice of hiring professors on the basis of research ability and of rewarding them exclusively on their performance as researchers. The only means of providing our students with an effective design education is therefore for current faculty members to develop these qualities.

This challenge is significant but not insurmountable. Billington has described the profound positive impact that Professors Wilhelm Ritter and Pierre Lardy had on the future design practices of their students, including, respectively, the great designers Robert Maillart and Christian Menn.[14] Yet neither Ritter nor Lardy had ever practiced design. Although these men were leading academics of their day, they were aware of the importance of their role as educators of future generations of designers and taught their students accordingly. Billington describes Ritter's study tour of the US in 1893 and subsequent book on US bridge design practice,[15] which is one way a professor without design experience could acquire a body of knowledge of what was at that time the pinnacle of bridge design practice. Billington also points out how Lardy consistently exposed students in his lectures to his deeply held values with regard to good structural form.

Ritter and Lardy are important examples of how professors who lack practical experience can develop the qualities necessary to teach design well. What is required, therefore, is for universities to provide the necessary conditions for current faculty members to develop these qualities. Given the entrenched culture of academia, there are certainly many reasons to regard this prospect with pessimism. Universities have, however, invested considerable resources in recent years to create the "design-friendly" curriculum. There is thus the willingness to improve the effectiveness of design education but a flawed vision of how to bring about these improvements. By redirecting these resources towards initiatives founded on the principles defined in this article, this investment would have a much greater likelihood of success.

Given the current financial uncertainties in the developed world and the importance of works of structural engineering and other infrastructure as enablers of a vibrant economy, it is now more than ever important that engineers serve society by creating value. The next generation of engineers must be given the knowledge, skills, and values they need to rise to this challenge. For this to happen, universities need to shift their focus from the creation of innovations to the education of innovators.

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UNDERSTANDING CREATIVITY

Eric M. Hines

Professor David Billington is engineering's greatest storyteller. Emphasizing the human character of engineering, his scholarship on great engineers and their work has transformed antiquarian subjects into relevant and surprising lessons on "the grand tradition of modern engineering." Where complex mathematics were thought fundamental to engineering success, Professor Billington demonstrated that many great works of engineering were based on astoundingly simple calculations. Where engineers were assumed to be driven toward one best solution, he demonstrated that engineers have always made choices between many possible solutions. These solutions grew from the imagination and courage of individual engineers working within specific social, economic and historical contexts. Where the industrial revolution was assumed to have severed the relationship between thinking and feeling, he demonstrated that the greatest works of structural engineering often resulted from conscious aesthetic choices by their designers.

Many of Professor Billington's stories explain how engineering's human character has remained consistent in our modern era, notwithstanding our technological progress. To study the human character of engineering through great works is to learn about engineering creativity. Beginning in the tradition of Professor Billington, with the stories of two bridges, this essay aims to address the concept of creativity directly. In doing so, I wish to claim the word "creativity" for engineering.

Three interrelated questions drive this discussion: What does it mean to engineer well? How do we use this knowledge to enrich our own lives and the lives of our children? And how do we inspire and educate our children to become great engineers? These three questions are related, and they suggest the importance of discussing this subject on three levels: the world historical level, which defines quality and sets the standard by which we measure all other work; the professional level, which holds the tension between our ideals and the reality of a given context; and the educational level, which engages the nature of fundamental understanding as it seeks to help young people develop judgment and distinguish fundamental principles from mere facts.

I will begin this discussion by introducing two ideas that can be seen clearly in the work of two great 20th century structural designers: Robert Maillart (1872-1940) and Jörg Schlaich (b. 1934). The examples I have selected are short span bridges, lesser known for their finished condition, but exemplary for the insight they provide into process. Robert Maillart's calculations for the 1925 Valtschielbach bridge exemplify the idea of *conceptual transparency*—a phrase that I use to describe fundamental understanding in its simplest possible form. Jörg Schlaich's sketches for the Ingolstadt bridge exemplify the idea of *drawing as a language*, or as Karl Culmann (1821-1881) described it, "the language of the engineers."[1]

Following this glimpse into the processes of great structural designers, I will attempt to describe the discipline of creativity, i.e. the part of creativity that can be taught. The creative process consists not only in imagining ideas, but also in expressing them through language and in judging their fitness. These actions of imagining, expressing and judging ideas require human engagement across an entire spectrum from intuition and openness to detailed analytical critique and judgment. Some scholars might call this the spectrum between divergent and convergent thinking, however I prefer to use the words *imagination*, *expression* and *judgment* because these words feel more alive to me. Central to this understanding is the idea of language as our means of expressing ideas. We tend to understand language as words, however drawings and mathematics also form languages that are essential to expressing what we imagine as engineers.

In order to provide more detailed insight into a specific creative process, I will discuss my own work on the structural design of the Wind Technology Testing Center (WTTC) in Charlestown, Massachusetts. Talking about this process at the level of a practicing professional allows me to draw attention to key moments that are perhaps more subtle and ordinary than those we know from works of world historical significance. This discussion will help to bring the details of process down to earth. It will also help to establish continuity on a spectrum ranging from student work to the great works. In my experience, the nature of process itself is relatively consistent on this spectrum. In the context of my own work, I will also argue the possibility for an engineer to be conscious of the ideals of structural art: efficiency, economy and elegance, not only in a masterpiece, but in all designs. This argument may also explain my attraction to lesser works by the great designers. These works may not be considered masterpieces, but they nevertheless demonstrate important details related to process that are less visible in the history of more famous work.

In the interest of achieving some level of generality in these ideas, I will then discus the education of university students in engineering design. I will focus on the idea of drawing as a language in the context of a steel design course in the third year of the Tufts undergraduate curriculum. Two examples drawn from my own practice will illustrate the ability for drawing to function as a language which can be abstract and analytical or literal and visual. In the first case, drawing takes the place of mathematical analyses for variations on the theme of a cantilever with one or more backspans. In these examples, an expert sees one fundamental behavior at work, whereas students typically believe that they see as many kinds of behavior as there are examples. In the second case, hand sketches completed during a coordination meeting with multiple participants illustrate the potential for working effectively in real time with collaborators through the language of drawing. The ability to draw an idea and its corresponding details during a meeting saved weeks of coordination effort that would have been required had basic decisions been deferred to further, independent study.

Conceptual Transparency

While the following calculations and sketches were instrumental in the creation of sophisticated structures, they are themselves quite clear and simple. In a world enamored of complexity and computational power, where high-tech is often equated with intellectual merit, they demonstrate a higher level of thinking—one that radically distinguishes the essential characteristics of a system from the trivial—conceptual transparency. This power of abstraction serves a vital role in the design of large-scale structures, where failures are catastrophic and experimental prototypes are prohibitively expensive. Civil engineers typically have one chance to get it right. Overlay this warning with the imperative of economy and the desire for beauty, and it becomes clear that conceptual transparency addresses equally the need to assume responsibility and the opportunity to work creatively.

We value Robert Maillart's work as much for its clear expression of engineering process as for its inherent quality as structural art. Robert Maillart was educated in the early 1890s under Wilhelm Ritter (1847-1906) at the Swiss Federal Technical Institute, or Eidgenössische Technische Hochschule (ETH), in Zurich. As successor to Karl Culmann, Ritter fulfilled Culmann's ambition to express analytical concepts graphically, and brought structural design education at the ETH to its high point in the 19th century. Ritter not only emphasized fundamental understanding of structural behavior but also discussed structural systems and details both in terms of their constructability and their appearance. Maillart spent his early career as a designer and builder, developing a series of bridges that defined the structural, constructive and visual potential of reinforced concrete. During this time, Maillart worked closely with Ritter on the full scale evaluation of completed structures, such as his 1901 Zuoz bridge.

From Professor Billington's scholarship on the life and work of Robert Maillart we not only learn about the designer himself, but also about his process. For instance, Maillart was exposed to the notion of deck-stiffening as a student of Wilhelm Ritter.[2] He internalized the idea of bending compatibility between arch and deck based on observations of cracks in his 1912 Aare River bridge.[3] And before arriving at his simple calculations for the Valtschielbach deck-stiffening he had developed more complex calculations for the 1923 Flienglibach bridge.[4] The relatively small scale of Maillart's structures makes them accessible to most

Figure 1

Robert Maillart's 1925 Valtschielbach Bridge, in Donath, Switzerland. [Princeton Maillart Archive]

engineers. Maillart sublimated work that otherwise would not have merited distinction. He made it clear that in the hands of a structural artist, the same bridge could achieve a level of quality far beyond mere usefulness.

We value Jörg Schlaich's work because it provides contemporary examples of structural art at its finest. Whereas most structural artists designed independently and constructed their own work, Schlaich has demonstrated that it is possible to create structural art as an engineering consultant in collaboration with architects. For this reason, Schlaich's work offers insight into process that is consistent with contemporary culture. Schlaich was educated in the strongest tradition of structural engineering to emerge from Post World War II Germany. In his thirties he led the design of the 1972 Munich Olympic Stadium for the firm of his mentor Fritz Leonhardt (1909-1999). Shortly thereafter in 1974, Schlaich assumed Leonhardt's professorship at the University of Stuttgart, and in 1980 he founded the office of Schlaich, Bergermann and Partners in Stuttgart with the team of engineers and staff who had worked together to build the Munich Stadium. The core of

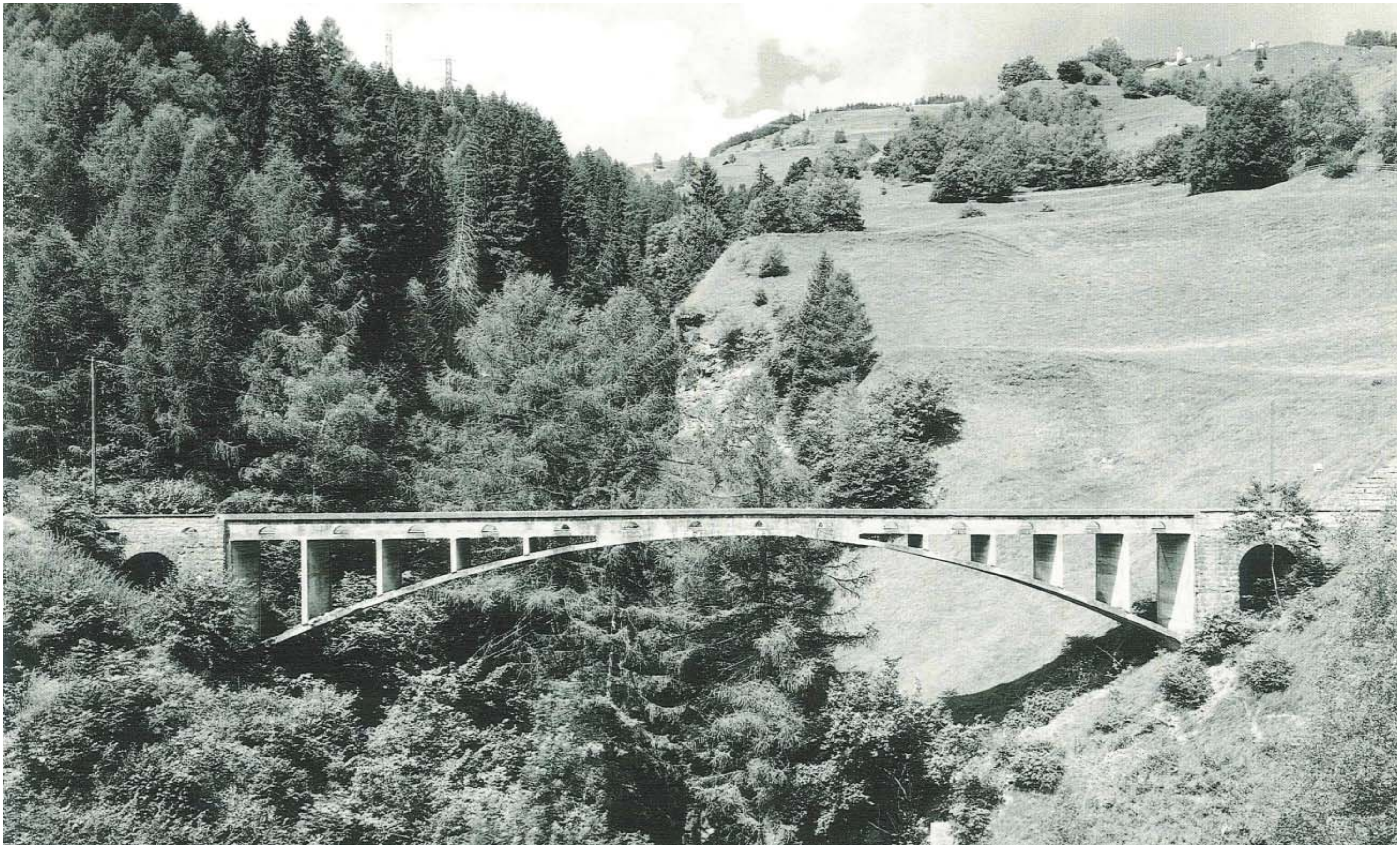
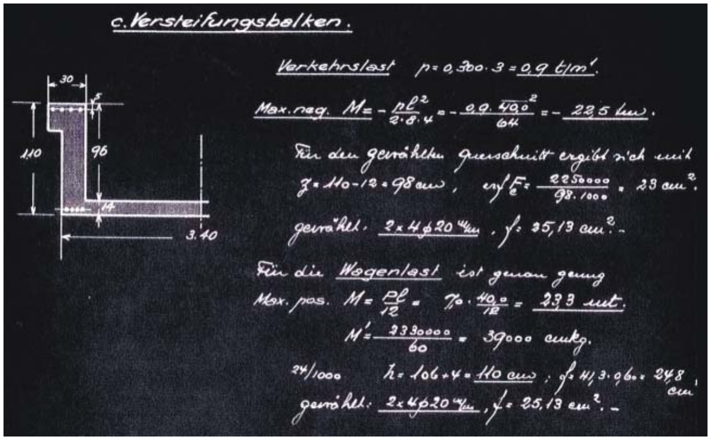


Figure 2

Robert Maillart's deck stiffening calculations for the Valtschielbach Bridge. [Princeton Maillart Archive]



this team continued to work together for the rest of their careers. Schlaich's major contributions include not only design innovations such as the cable net wall and the glazed grid shell, but also the development of steel castings and cable structures, the legitimation of the pedestrian bridge, the development of strut and tie methods for reinforced concrete, and the development of renewable energy resources from solar chimneys to parabolic mirrors. Schlaich defined what it means to be engaged as a structural engineer in the late 20th and early 21st centuries—a designer motivated by social conscience, who uses the best tools of research and analysis to push the limits of structure and realize new forms.

Robert Maillart's Valtschielbach Bridge

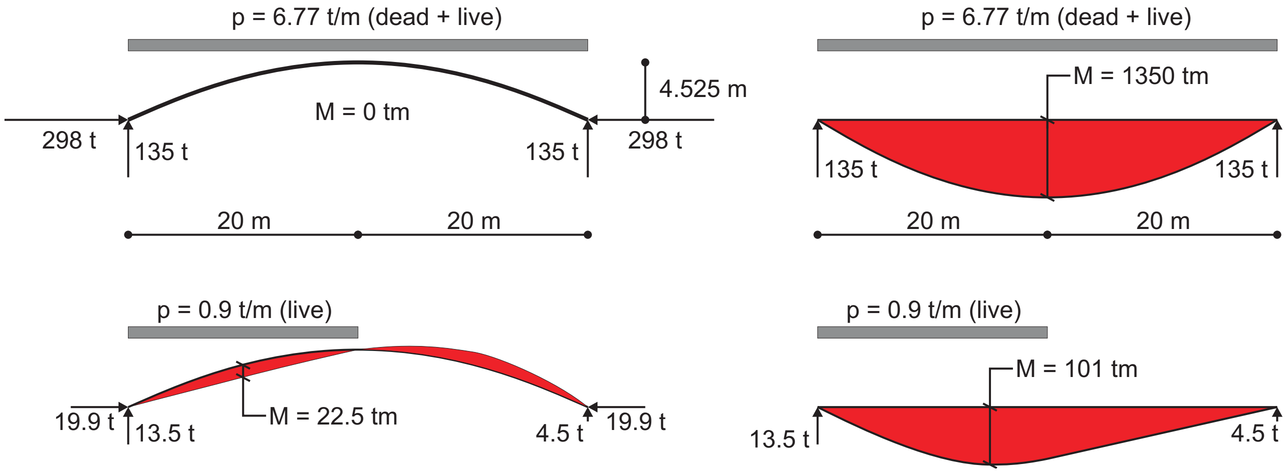
For me, Robert Maillart's most compelling calculations stand behind his 1925 Valtschielbach Bridge in Donath, Switzerland, shown in Figure 1. At their core is a simple algebraic equation, derived according to static equilibrium. There is nothing special about the mathematics. Yet the assumptions behind Maillart's mathematics and the resulting design conclusion represent the highest level of engineering thinking. These calculations demonstrate that our chief concern as engineers is the quality and significance of our assumptions for a particular case, not the generality of our analytical tools. In Professor Billington's words:

> Robert Maillart, the Swiss bridge designer, developed in 1923 a limited theory for one of his arched bridge types which violated in principle the general mathematical theory of structures and thereby infuriated many Swiss academics between the wars. But Maillart's limited theory worked well for that special type of form. Within that category of type, Maillart's theory was useful and had the virtue of great simplicity; he developed the theory to suit the form, not the form to suit the theory. In the United States, by contrast, some of our best engineers understood the general theory well, but not understanding Maillart's specific ideas, they failed to see how new designs could arise. They were trapped in a view of an engineering analysis which was so complex that it obscured new design possibilities.[5]

Adherence to a general theory in this case is tantamount to the blind application of equations so often observed in the work of engineering students. Maillart's much simpler approach, however, with its emphasis on new possibilities for arched bridge forms, represents the heart of creative engineering thinking—creativity not only with respect to the appearance of form, but also with respect to its engineering substance. Even Maillart's calculations were creative. In other words, Maillart recognized that there was more than one way to approximate the structural behavior of his deck-stiffened arch systems, and he chose an approximation that exhibited a high degree of conceptual transparency. In the appropriate context, Maillart's calculations were entirely correct. That was precisely what angered Maillart's academic peers, and distinguished Maillart's engineering thinking. Maillart's calculations for the deck-stiffened Valtschielbach bridge total 3 ½ pages. The calculations representing Maillart's conceptual leap filled the last half page, and are shown in Figure 2.

Figure 3

Valtschielbach arch bending moments compared to simple beam bending moments.



Seldom has the point been made more clearly that the engineering genius of the work rests on the assumption supporting this half page, and not on the calculations themselves. Based on the full scale behavior of his previous bridges, Maillart assumed that the deck and the arch deform together, and would thus carry bending moments in proportion to their flexural stiffnesses. Maillart designed the deck to be significantly stiffer than the arch and thus to carry most of the bending in the system. Such a conceptual leap reflects the same level of intellectual quality as the creation of any general theory, and far surpasses the technical exercise of applying such a theory. From a human point of view, Maillart's conceptual leap exceeded the generalized theory in value, because it led to more economical bridges that have become artistic icons. Many of these bridges are still in service.

The essence of Maillart's engineering calculation in Figure 2 for the Valtschielbach bridge is represented by the equation

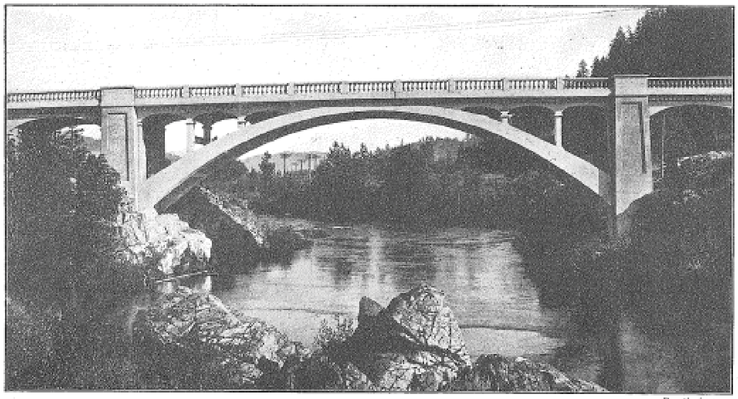
$$M = \frac{pL^2}{2 \bullet 8 \bullet 4} = \frac{(0.9\ t/m)(40\ m)^2}{64}$$

In order to understand this calculation, it is helpful to discuss the Valtschielbach bridge with respect to two other structural forms: a simple beam and an American arch of similar vintage. Comparison with a simple beam places the potential efficiency of the arch form in perspective. Maillart designed the arch in its funicular form under dead + live load uniformly distributed along the span. The resulting static equilibrium is shown in the upper left image of Figure 3. Under this load case of approximately 6.77 t/m, he proportioned the arch to be 3.4 m wide and 23 cm deep at the crown, resulting in an axial stress at the crown of 35 kg/cm^2 (500 psi).

By contrast, these loads on a simple beam would induce bending moments on the order of 1350 tm, as shown in the upper right image in Figure 3. The moment demands on Maillart's arch, however, were 60 times smaller for two reasons. First, only the unbalanced live loads were expected to produce bending moments in the arch. These live loads were 0.9 t/m, and hence very small in comparison with the total loads. Second, the bending moments in a three-hinged arch under unbalanced live loads can be estimated to be $pl^2/64$ as opposed to $pl^2/8$ for the uniformly loaded simple span. Combining the effects of lighter loads with the reduced bending moment results in a drastic reduction of

Figure 4

American Arches featured by McCullough and Thayer in 1930.



Frontispiece

A rather plain yet pleasing example of rib arch design. A flat parabolic rib sprung from solid rock walls. (Over the Rogue River near Gold Hill, Oregon.)

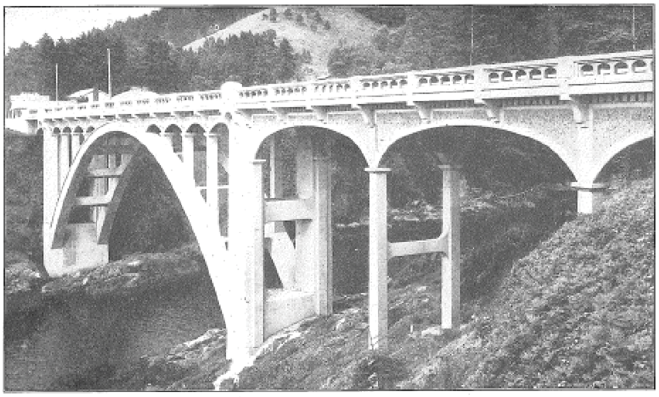


Fig. 13.

Curved approach girders, a dentil and bracket treatment, and the employment of bush hammered panels relieve the monotony of this open spandrel arrangement. (Depoe Bay, Lincoln County, Oregon.)

bending demands on the arch:

$$\frac{M_{arch}}{M_{beam}} = \frac{p_{live}}{p_{total}} \bullet \frac{M_{arch}}{M_{beam}} = \frac{0.9\ t/m}{6.77\ t/m} \bullet \frac{1}{8} = \frac{1}{60}$$

The lower images in Figure 3 depict the same arch and simple beam under uniform live loads on half the span. Under unbalanced live loads only, the bending moments in the arch are still 22% of what they would be in the simple beam. This can be explained by the fact that the deformed shape of the arch experiences a point of inflection at the crown. This deformed shape has an appearance similar to the moment diagram drawn in the lower left image of Figure 3. Since half of the arch bends upward, the maximum moments are lower than in the beam which bends down along its entire span. Another way to understand this behavior is to consider the effects of the horizontal forces in the arch. Bending moments in the arch resulting from vertical forces alone are identical to the moments in the simple beam. The horizontal forces at the abutments subject the arch to bending moments that oppose those induced by the vertical forces, effectively reducing these moments to their final values in the arch.

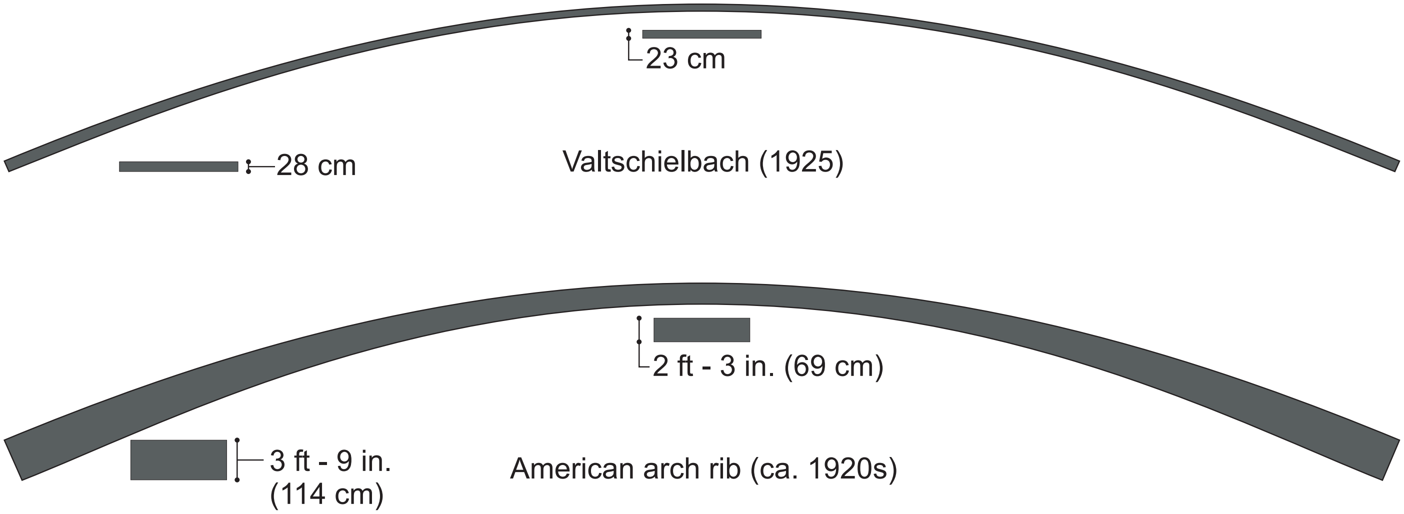
While comparing an arch to a simple beam says much about the potential efficiency of an arch system, it does not explain what distinguished Maillart's Valtschielbach bridge from other arch bridges of the time. In order to understand this, it is more helpful to compare the Valtschielbach bridge to an American arch bridge of similar span, rise and vintage.

For this purpose, I would like to reference a 1930 textbook entitled *Elastic Arch Bridges* written by McCullough and Thayer.[6] Conde McCullough was the Assistant Chief Engineer of the Oregon State Highway Department, and Edward Thayer had been the Senior Bridge Engineer of the San Francisco-Oakland Bay Bridge. Since these two men were accomplished bridge engineers, their book gives special insight into the cultural pull of analysis on 1920s American engineering.

Figure 4 shows two of the arches featured in McCullough and Thayer's book. Unfortunately, the authors did not give dimensions for these arches. Their images, however, convey the basic form of American arch designs, and their captions are informative. The bridge on the left is described as "A rather plain yet pleasing example of rib arch design," while the bridge on the right is described in the following way: "Curved approach gird-

Figure 5

Valtschielbach Arch thickness compared to an American arch of similar dimensions.

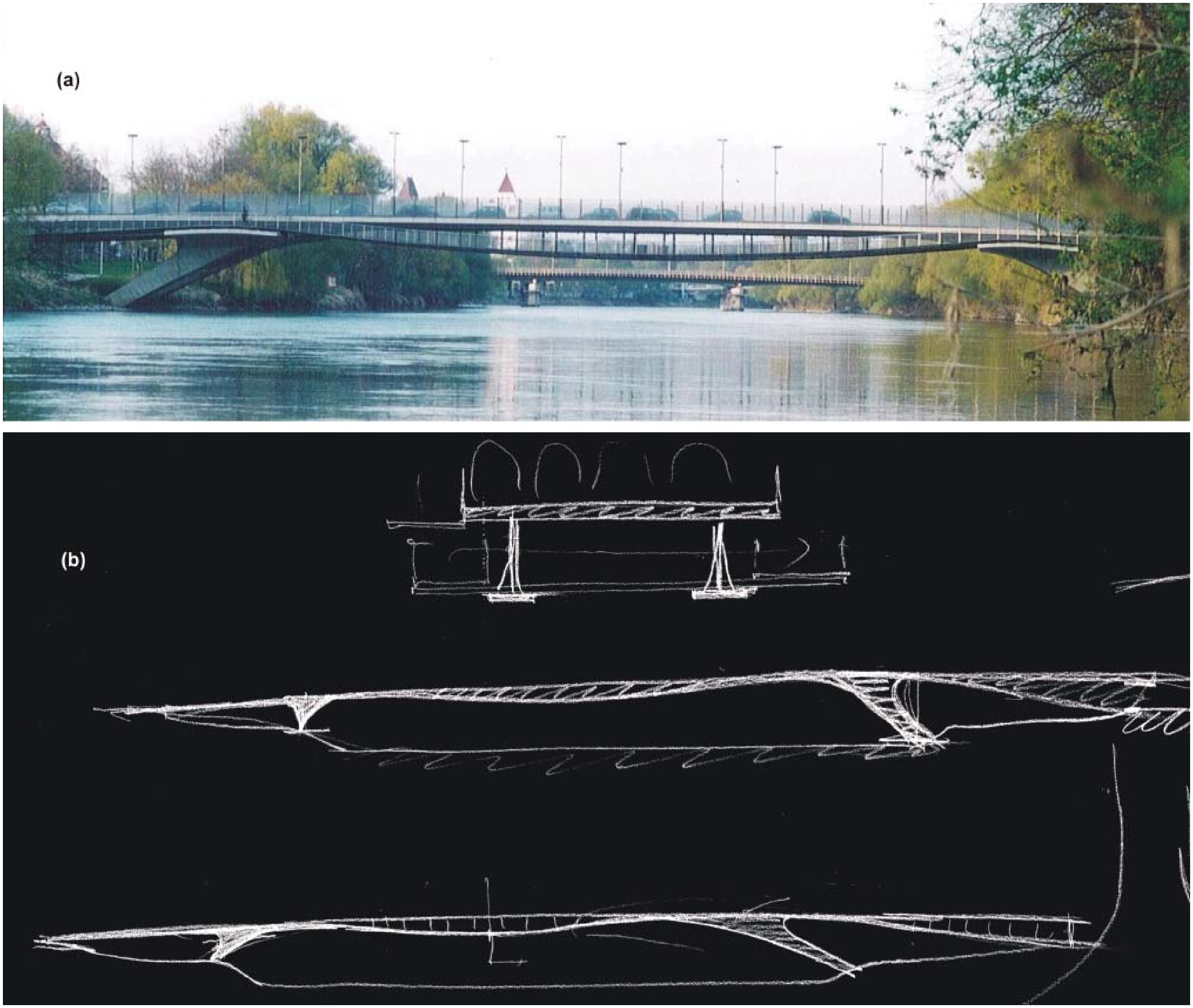


ers, a dentil and bracket treatment, and the employment of bush hammered panels relieve the monotony of this open spandrel arrangement." The bridges are not considered as unified designs either analytically or aesthetically. McCullough and Thayer's book focuses on the theory of arch design and contains only sparse reference to actual designs. When designs are referenced, they are not presented as designs, but as opportunities to illustrate the theory at hand. The authors themselves seem to convey that visually an arch is no more interesting than a beam, and the rest of the bridge requires various "treatments" in order to break the monotony wrought by such a structure.

In a table with arch rib dimensions of several American bridges, McCullough and Thayer listed seven bridges ranging from 128 ft to 132 ft in span—similar to the Valtschielbach bridge. Of these seven, one bridge is listed with a rise of 15 ft, also similar to the Valtschielbach. The roadway width for this bridge is listed as 24 ft, and the bridge is described as an open spandrel design with two ribs. Since the Valtschielbach bridge is approximately half as wide as the American bridge, it is not unreasonable to compare the Valtschielbach arch to one of the American bridge's ribs. Figure 5 compares the thicknesses of the Valtschielbach and the American arches, each drawn at the same scale. The 9 ft – 0 in. wide American arch rib has a crown depth of 2 ft – 3 in. (69 cm) and a spring point depth of 3 ft – 9 in (114 cm), whereas the 3.4 m wide Valtschielbach arch has a crown depth of 23 cm and a spring point depth of 28 cm. The three primary differences between these two designs are the fact that the American arch was probably designed to take fixed end bending moments at the spring points, take all of the bending without cracking, and gather up the arch structure into a rib rather than spread it out as a slab. Gathering the material into deeper ribs makes sense if a designer wants to provide the ribs with sufficient depth to resist bending stresses without cracking. While this particular American arch rib is relatively wide, McCullough and Thayer listed other bridges of similar span with ribs up to 6 ft thick and 3 ft – 6 in. wide at the spring points. American arches of the time were designed according to elastic theory, which often assumed an uncracked section for the sake of linearity. Similar to McCullough and Thayer, Hardy Cross emphasized the importance of this simplifying assumption and its design implications in the face of relatively complicated elastic theory calculations.[7] Ultimately, this approach led to arches designed as curved beams.

Figure 6

Danube River bridge in Ingolstadt. (a) Elevation. (b) System concept sketches.



In spite of the importance these engineers attached to simplifying assumptions, the cultural pull toward complicated theory was too strong to resist. Perhaps this resulted as much from a misunderstanding of the creative process as from a fascination with elastic theory. As Professor Billington discussed in Chapter 9 of *Robert Maillart's Bridges*, the American emphasis on analysis and elastic models prevented academics and designers alike from seeing the potential for elegant structural forms.[8] Conversely, Maillart's close observations of his completed bridges, his focus on system behavior, and his design-oriented education under Wilhelm Ritter led to the assumption that the arch and the deck bend together. For this reason, as the deck was stiffened with respect to the arch, it would assume more bending until the arch experienced negligible bending demands.

Jörg and Michael Schlaich's Ingolstadt Bridge

Figure 6(a) shows the third bridge over the Danube River in Ingolstadt, Germany, which won a design competition in 1993 and was completed in 1998. Jörg and Michael Schlaich generously allowed us to photocopy many sketches from their collaborative design process for this bridge with Architects Kurt and Peter Ackermann. These sketches and several interviews formed the basis for our story of this design process and the design competition published in 1998.[9] In the discussion of conceptual transparency, these sketches complement the simplicity of Maillart's Valtschielbach calculations by demonstrating the power of drawing as a language.

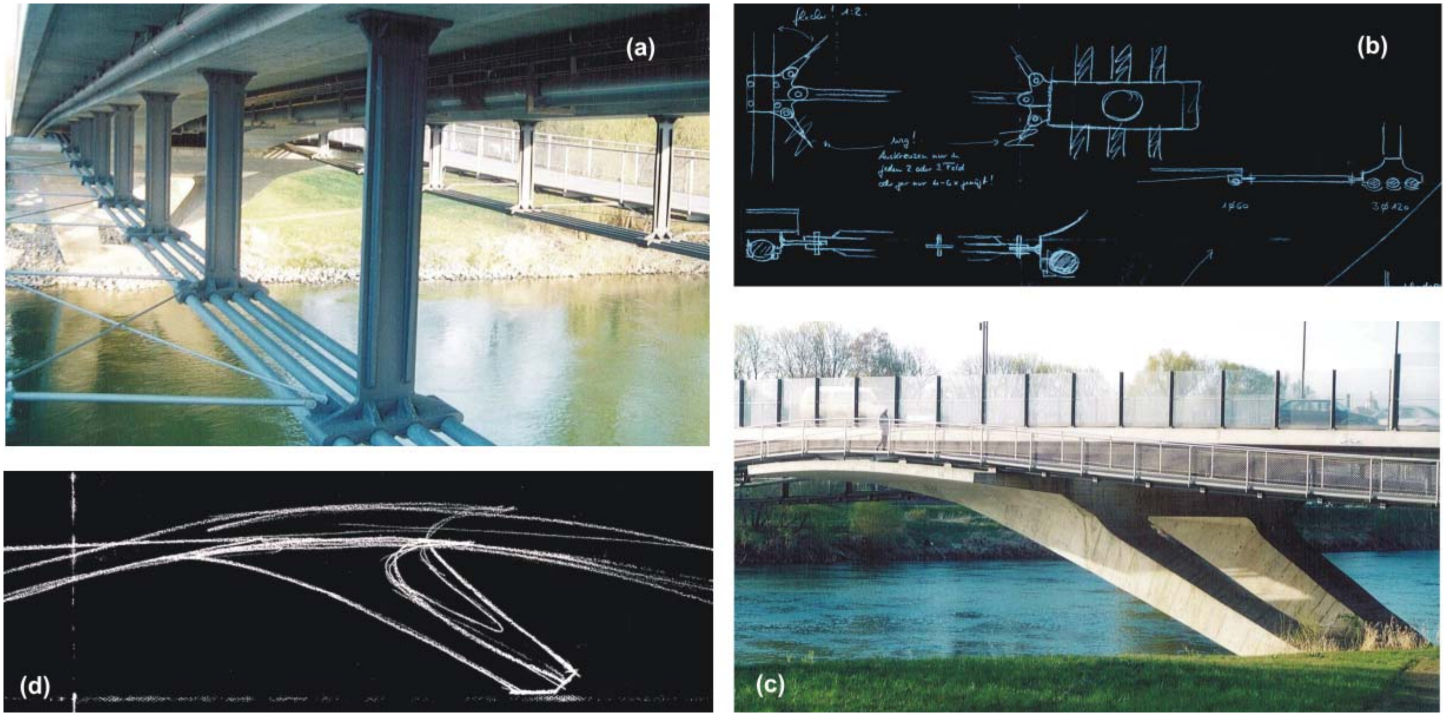
One of the important early system sketches is pictured in Figure 6(b). While simple, this sketch captures the essential ideas of the proposed system: a slender deck, supported as an inverted suspension span, and longitudinally prestressed by the arching action between two raked piers. The separation between the road and the pedestrian can be seen in the section at midspan. The second elevation below shows a representation of massing with vertical supports between the cables and deck. The sketches are executed quickly in the company of collaborators. They are the standard means of communicating between designers. Yet, it is rare that we consider closely and discuss such sketches that represent the creative process. They are often considered either to stand alone as a flash of genius or to be mundane in their multitude. Representing hundreds of sketches developed during a design process, the sketches in Figure 6(b) and in Figure 7 show the kind of communication that is essential to the creative development of an idea in structural engineering.

Figure 7 shows this communication in further detail. It is not enough simply to sketch a system. The system relies on its details, and conceptual transparency is largely concerned with the interaction between a system and its details. Figure 7(a) shows the supports between the cables and the deck, along with the horizontal ties between these cables and the pedestrian walkway. Figure 7(b) shows sketches of these details that were developed in close proximity to the sketches in Figure 6(b). Figure 7(c) shows the skewed support, which evolved to retain a high degree of plasticity from a very simple decision to skew the supports by 20 degrees. Figure 7(d) shows the early conceptualization of this support as a plastic element.

The examples set by Figure 6(b) and Figure 7 imply that the creative work of engineers involves intense communication between ideas for a system and ideas for its details. This communication poses a challenge, because it is easier to fall into a habit of focusing only on the big picture or only on the details. The sketches in a design process need to be effortless because they need to be disposable. The value of any given sketch resides in its relation to all the other sketches and to the design process as a whole—not in its quality as an independent work of art. The disposable nature of these sketches gives them their value—they record fleeting thoughts and ideas, set down quickly for the purpose of critical evaluation and discussion. To produce them fluently is to speak the language of the engineer. Leonardo Da Vinci's sketch books are compelling precisely because they exhibit his artistic talent not for its own sake but as eloquence in the language of drawing. Often these sketches are accompanied by simple calculations and

Figure 7

Ingolstadt details and concept sketches. (a) deck support on cables with bracing to pedestrian walkway; (b) concept sketches for connections between deck support cables and pedestrian walkway; (c) skewed pier with deck and pedestrian walkway; (d) pier sketch.



text. Their value lies in their ability to represent clearly and accurately a dynamic process that is invisible to most students in its human character—composed of sketching, simple calculations, discussion, debate and an iterative approach to the development of an idea. I tell my students that if our imaginations were perfect, we would not need to concern ourselves with the discipline of creativity. Our ideas would come fully formed out of our imaginations. In the real world, however, most of us harness the power of our ideas by communicating about them. We communicate with ourselves, with our colleagues, and with our critics. In this communication, we learn more about our ideas and develop them further. While it may not be possible to teach creativity per se, it is certainly possible to teach the discipline required for creative work to flourish.

The Creative Process

Engineers ought to understand their work as creative because it requires choices. If there is more than one way to do something, creativity comes into play. The creative process can be understood to consist of three stages:

1. An idea is *imagined*: and exists in the imagination only.
2. It is *expressed* in language: drawings, words, mathematics.
3. Only then can it be *judged*: through thought, feeling, and discussion.

The imagination, expression and judgment of many ideas proceed iteratively and in parallel. Modes of expression may change over the life of an idea, people may alter their judgments, and the idea itself may evolve. The creative process becomes an artistic process when expression is intended to evoke an emotional response. Understood in this way, Engineering, Mathematics, the Arts, the Humanities and the Sciences need not vie for superiority. They are all creative endeavors, each with distinct intentions.

Understanding creativity as a process of choice-making brings it down to earth without corrupting its essence. Creativity does not belong to inventors and artists alone. Common themes between the lives of creative individuals are the courage and effort with which they engage the creative process. If the creative process is misunderstood as consisting of its first two stages only, imagination and expression, the result is a fundamental lack of rigor. When engineers recognize that the rigors of judgment are as essential to creativity as the openness of imagination, they can learn to withhold judgment of an idea until it has been appropriately expressed. Inability to recognize the place of rigor within a larger process leads many engineering students to short circuit this process. They believe that ideas come into being fully formed. Therefore, they must solve each problem correctly on the first try. This prejudice robs students of their courage.

A student once asked me where ideas come from. I replied that I do not know, and that I think of ideas as gifts. I also related, however, my experience that ideas come richer and in greater number when I am engaged in a process. I told her that where I begin my process often doesn't seem to matter, so much as that I try to focus on what I want and then try to stay open to new ideas as they come. In the process of expressing and judging my initial ideas, I learn quickly. Soon enough, new ideas come, often unexpectedly, and rarely when I am sitting at my desk. I reserve my time at my desk for expression and judgment. When it comes to my imagination, I simply try not to get in my own way.

In my conversation with my student, this description of my experience ended with the advice that she ought not to worry about her ideas. They would come, but only on the condition that she was fully engaged in the work of imagining, expressing and judging. In addition to relating my own experience, I discussed the process behind Maillart's Valtschielbach bridge (described earlier in this essay). The moment at which Maillart developed his calculations was less important than his process of preparing for that moment. This process spanned decades: from his time as a student under Wilhelm Ritter, to his construction of the 1912 Aare River bridge, to the early 1920s.

I have continued to appreciate my student's honest question, and I felt a sense of satisfaction as I watched her own ideas develop in the midst of her process and the process of her design team. One of the most compelling conclusions drawn by her and her teammates three months later was that originality was less important than they had first thought. In their final presentation, they told a wonderful story about how their desire to produce good work eventually overshadowed their concerns about where their ideas came from and who they came to. At this point, not only did they begin to feel more creative as individuals, but also they began to enjoy their work together. There was no question that regardless of where various ideas had come from, the created work belonged to them. For me, this realization is important because it challenges the harmful cliché of some genius imagining great thoughts *a priori*. Once my students gave themselves permission to engage a creative process (even though they were not feeling particularly like geniuses), and once they believed that the good ideas would eventually arrive (so long as they committed themselves to their process), their motivation to see the process through sustained itself.

Parts of the creative process can be taught, and parts of it cannot. The unteachable parts may be understood in terms of inspiration, talent and wisdom. The teachable parts may be understood as the discipline of creativity:

1. *Imagination*: it may not be possible to teach *inspiration*, but it is possible to share the development of one's own ideas honestly and transparently. It is possible to tell the stories of real engineers and artists. Educators who are present for their

students can create environments and share techniques that encourage them to think in new ways.
2. *Expression*: it may not be possible to endow *talent*, but educators can teach the use and meaning of fundamental languages such as drawings, words and mathematics. Educators can share examples of expression and discuss their effectiveness in the creative process.
3. *Judgment*: it may not be possible to teach *wisdom*, but it is possible to demonstrate it. Students can learn to think critically. They can learn how to understand their own feelings and the feelings of others. Students can learn the nature of responsibility by assuming responsibility.

The discipline of creativity accepts the necessity for iteration, and so requires engagement of the creative process with speed and courage. In this context "speed" is necessary to ensure that the expression of ideas is uninhibited and that judgments are disciplined. "Courage" is necessary to temper one's fears of expressing a bad idea or facing a tough decision. Since most engineering projects are the work of more than one person, individuals need to be aware of interpersonal interactions that can either fuel or inhibit the creative process. We should not shy away from the potential discomfort these interactions present. In doing so, we miss opportunities. Understanding the principles of the creative process provides strength to see the process through.

Drawing, the Language of the Engineers

The concept of drawing as a language was expressed by Karl Culmann in the mid 19th century as he developed graphic statics.[10,11] In Culmann's words, "Drawing is the language of the Engineers, because the geometric way of thinking is a view of the thing itself and is therefore the most natural way; while with an analytic method, as elegant as that may also be, the subject hides itself behind unfamiliar symbols." For this discussion, however, I would like to consider drawing even more broadly—as a language requiring multiple levels of abstraction, similar to words and mathematics.

Expression of thought through language is an essential stage in the creative process, and engineering requires the command of three primary languages:

1. *Words* communicate action and express ideas that cannot be seen.
2. *Mathematics* express quantity.
3. *Drawings* express substance or abstractions thereof—real objects and behaviors that are best understood by their appearance.

Contemporary American university culture clearly recognizes the value of words and mathematics as forms of communication. The act of acquiring a liberal education involves the extensive use of these languages. Drawing, on the other hand, has often been misunderstood as either artistic talent or a mere technical discipline. Understood as a language however, drawing is similar to writing, speaking and mathematics: it requires skill, but it also requires intellectual engagement.

Similar to written and oral communication, the audience matters. For presentation to an owner, realistic appearance is helpful. For communication with architects, realistic appearance is valuable, but can be tempered with abstraction and style in a manner that facilitates a collaborative process. For contractors developing an estimate, drawings should depict quantities and the general level of complexity. For contract documents sufficient detail to construct the work is required. Even with the most powerful computer modeling systems, experience and thoughtfulness are required to develop contract drawings that are clearly expressed and well coordinated. Providing information that is incorrect can be more harmful than not providing any information. In order to provide contract information in a manner that is consistent and easily understood by an expert, engineers have developed several abstractions such as weld symbols, elevation marks, tolerance

Figure 8

Inside the Wind Technology Testing Center (WTTC), facing the test stands to the west. The wind turbine blade shown mounted on the south stand is approximately 50 m long.

numbers and typical details. These abstractions, while often communicated in the form of drawings, are generally not comprehensible to a person who does not speak this language.

Among engineers, drawings form the heart of a process by which we come to understand the behavior of structural systems. In the next section, I will attempt to demonstrate some essential moments in a creative process from my own work. Drawings figure heavily in this process, and tell most of the story. The words in the following section are necessary only to describe the design team's actions, feelings and judgments about different ideas that were expressed in the language of drawing.

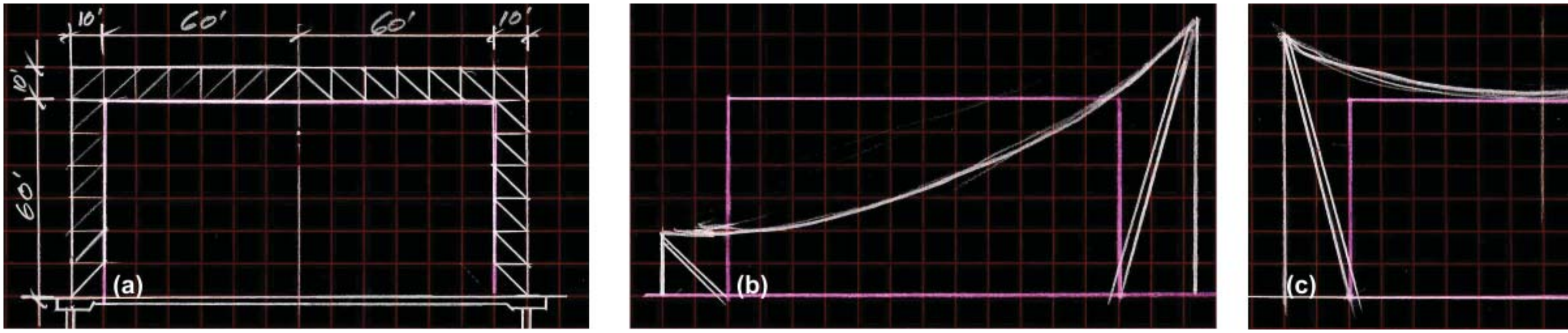
The Creative Process and the WTTC Trussed Frames

The recently completed Wind Technology Testing Center (WTTC), in Charlestown, Massachusetts provides an example from my own work where I can explain in greater detail the process by which the structure was conceived. This laboratory for testing off-shore wind turbine blades required an enclosure approximately 300 ft long, 140 ft wide, and 80 ft high.[12] Blades would be anchored to one of three posttensioned concrete test stands, shown in Figure 8, and tested as cantilevers either horizontally, vertically or biaxially. The dimensions and expected deformations of a 90 m blade determined the enclosure requirements. The laboratory also required two 50-ton cranes for handling the blades and mounting them to the test stands. The length of the lab being twice the width, plus the desire for potential future expansion in the east-west direction made three-dimensional framing or length-wise framing unattractive for this building. Early in the process designers and owners agreed that a modular, planar system made the most sense for supporting the enclosure.

Several early schemes for the enclosure responded to the fact that the blades would be anchored to the test stands at angles of up to fourteen degrees. If the roof of the facility were sloped upward

Figure 9

WTTC frame concept designs I (above).



from the test stands towards the blade tips, it would be possible to reduce the enclosure volume and surface area significantly. This would conserve cladding material, reduce the heated volume and provide some opportunity for expression in the otherwise simple exterior form of the building. Such a system would, however, limit the use of cranes in the facility, would necessitate two sets of runway beams for a high crane and a low crane, and would inhibit future vertical expansion of the test stands. Such a form would also require each bay of framing to be unique in its total elevation. While varying elevations would not necessarily pose a problem for solid elements, it would complicate attempts to develop truss columns with regular panel points.

Figures 9 through 11 show early concept sketches for the facility. All concept sketches were developed at similar scale and with reference to the required crane clearance envelope. The architect experienced some frustration with the brute fact that a simple box best suited the crane requirements. This frustration, coupled with the owner's desire to save money early in the project led to removing the cranes from the design altogether for approximately 3 months. Eventually, however, it was concluded that bridge cranes were an essential part of the facility. During this time, the conceptual studies in Figures 9 through 11 represented collaborative work by the architects and engineers to develop a regular system with a strong form. One form favored by the architects was the swoosh shown in Figure 10(a). As we developed this system to suite the span, we attempted to lighten the form by supporting the main span with a kingpost, as shown in Figure 10(e). Figure 11(a) shows an attempt to stabilize the structure by lateral bracing instead of the frame action depicted in Figure 10(d).

Once the system was to be stabilized laterally by braced columns, it became possible to lighten the connection between the roof truss and the column as shown in Figure 11(b). This scheme

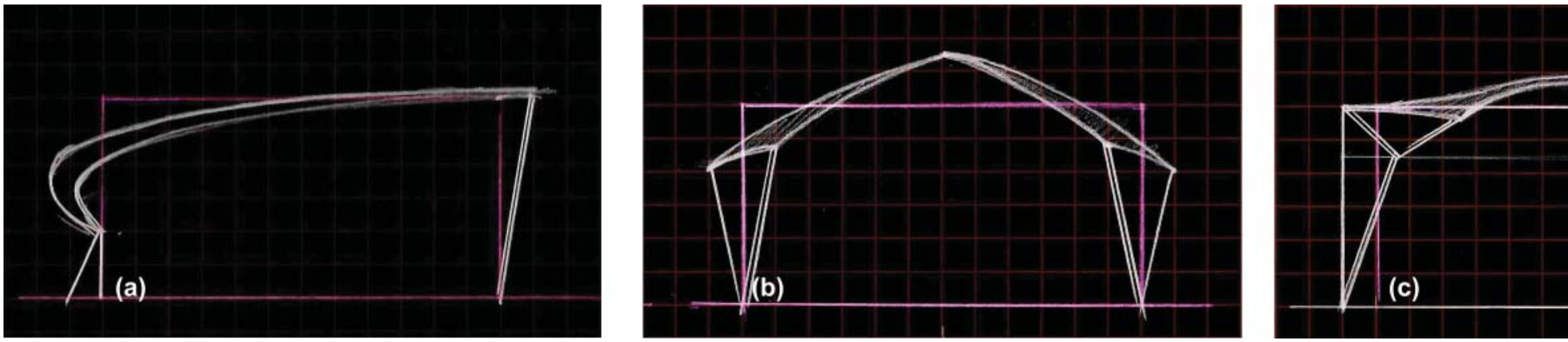
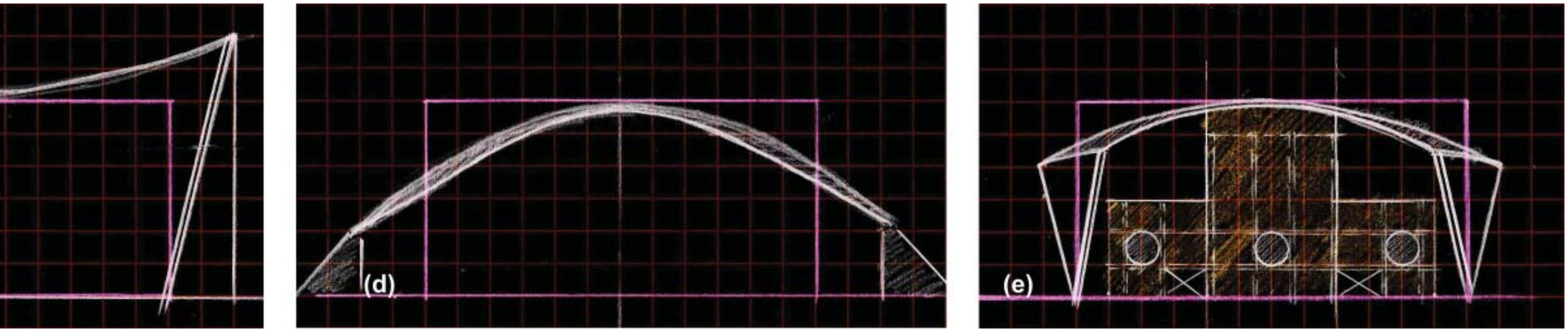


Figure 10

WTTC frame concept designs II (below).



maintained the exterior expressive quality of the swoosh, while behaving structurally similar to its symmetric counterpart in Figure 11(c). These roof schemes offered the potential for dynamic and interesting details, such as the one shown in Figure 11(d). In a final attempt to draw plastic expression out of the otherwise rigid program, each individual frame was rotated slightly about its south foot, resulting in a warped roof surface. Furthermore, it was possible to integrate the transverse and longitudinal column bracing on the north side by shifting the columns off their transverse axes. Both of these moves are shown in Figure 11(e). This figure also shows the crane columns as an independent structure inside the building.

It hardly needs to be observed that by this point the roof scheme had overwhelmed the structure and stolen focus from the main purpose of the enclosure—which was to give ample room to test blades, support bridge cranes with maximum flexibility, and allow the lab to be lengthened eastward in the future. Furthermore, the spreading column supports on the north side would result in significant additional foundation expenses, since this site required piles or shafts 160 ft down to bedrock.

During this process, the owner made clear that future flexibility of the lab was important to the facility. The largest blades in the world were currently on the order of 60 m. No 90 m blades were even under design at this point, let alone in production. While the wind industry could not imagine blade lengths exceeding 90 m, recent history had shown that blade lengths had grown exponentially over the past 20 years, in spite of continued expectations that blade lengths would eventually plateau. In light of this history, even 90 m could not be considered an absolute limit. While most of the schemes in Figures 9 through 11 were judged to be unrealistic for the lab, the general idea of a self-stabilizing, planar system allowed future east-west expansion by obviating the need

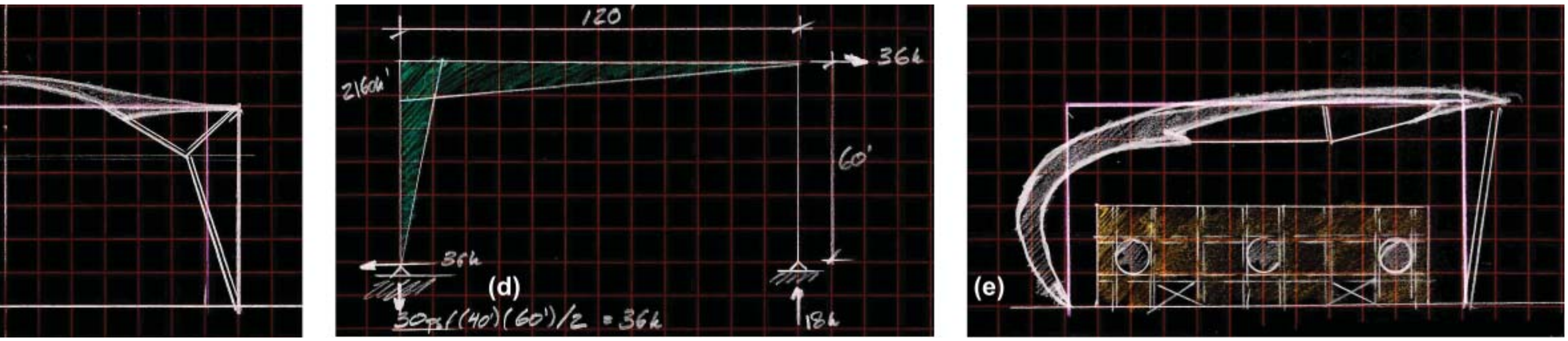
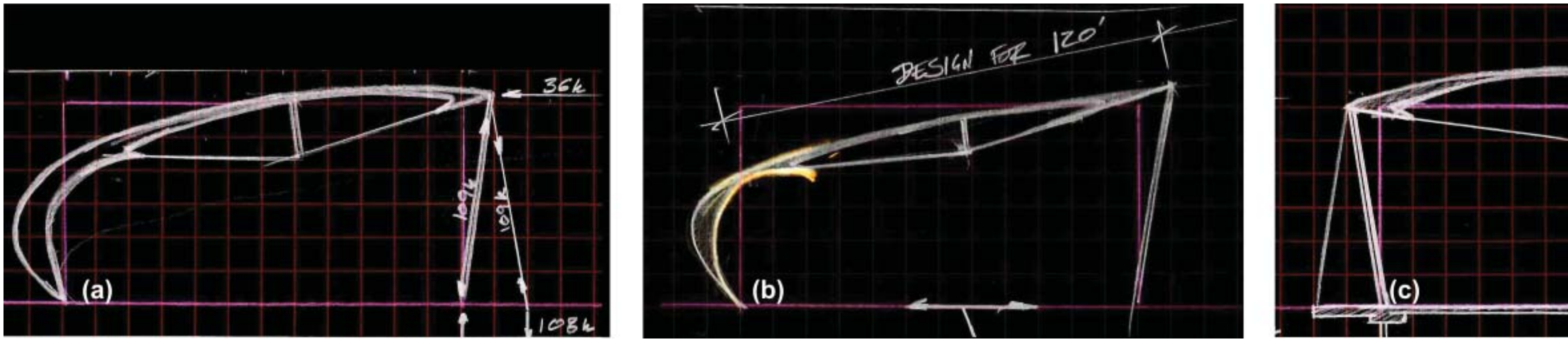


Figure 11

WTTC frame concept designs III (above).



for bracing on the east and west ends of the structure.

For initial pricing, the design team carried forward two designs: conventional 6 ft deep bar joists at 10 ft on center supported on girders and wide flange columns at 20 ft on center; and a series of trussed frames supported at 30 ft on center. The result of initial studies was that the two system costs were estimated within a few percent of each other. Some estimates even implied that the trussed frames would cost less than the joist system. The premium for fabrication at exacting tolerances would be offset by material savings and simplified erection due to a reduced number of pieces. Heavy grade beams, whose designs were dictated by laboratory testing requirements, offered stiff foundations to which the bases of the trusses could be fixed. This fixity helped to stiffen the frames while maintaining their slender 7 ft truss depth.

Figure 12 and Figure 13 show some of the studies undertaken on the form of the trussed frames once the system had been chosen.

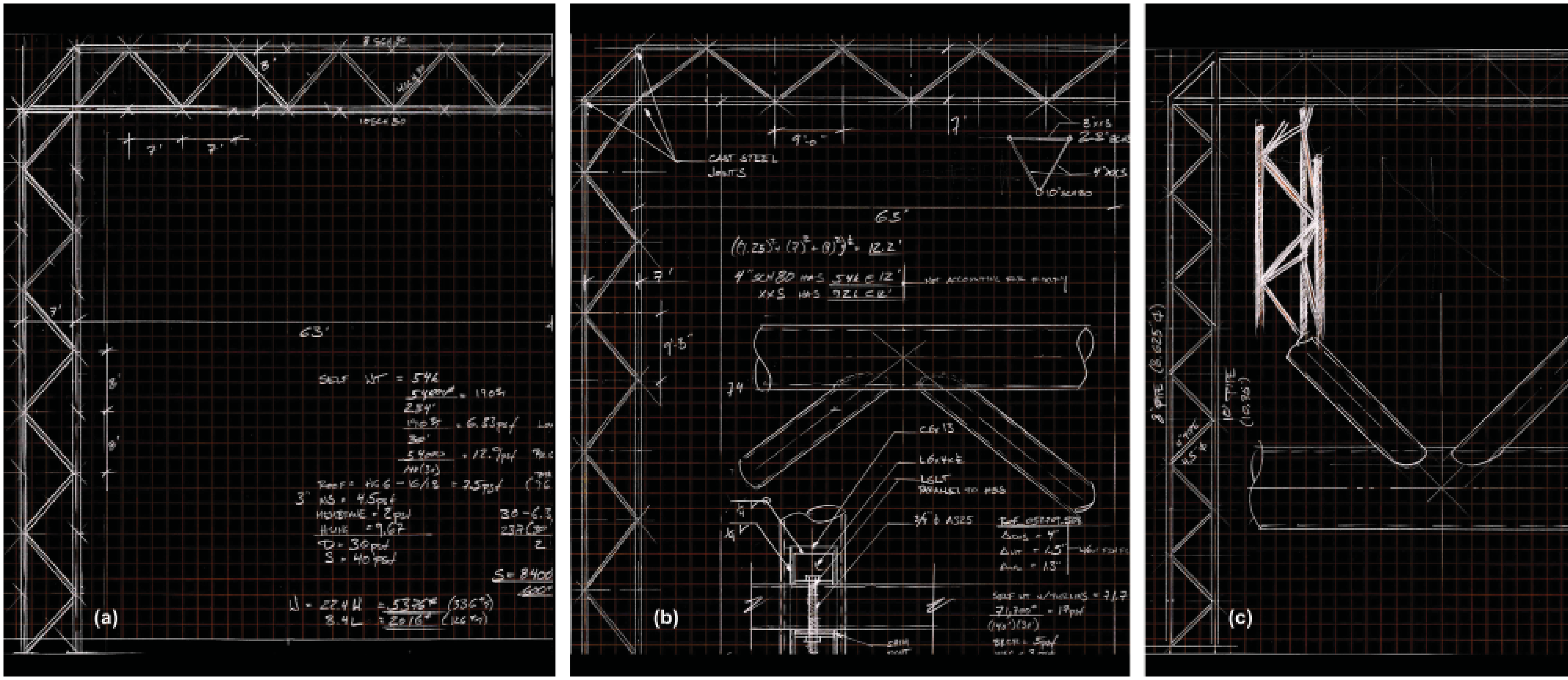
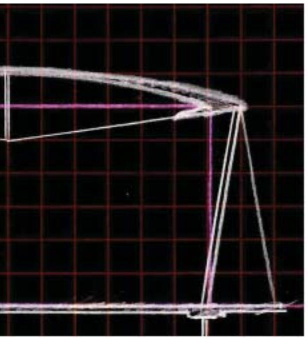
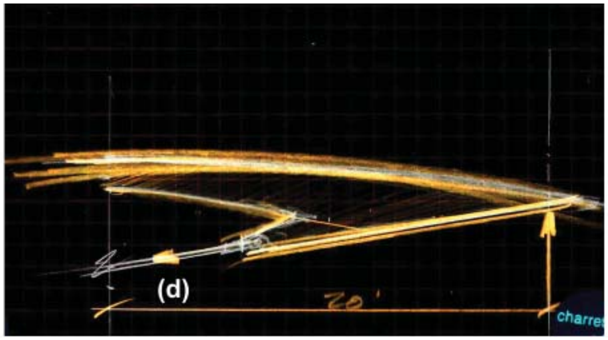
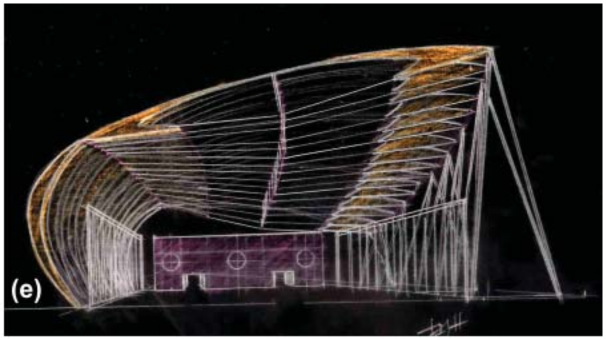


Figure 12

WTTC panel spacing and detail concepts (below).

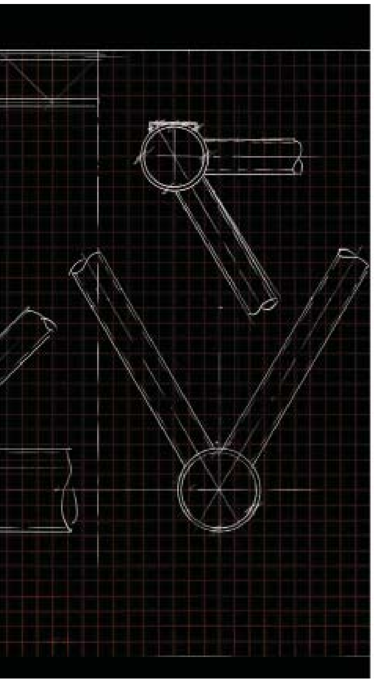






We decided to make the frames three dimensional for stability against lateral torsional buckling. This eliminated all out of plane bracing and achieved an elegant simplicity both in the erection and in the appearance of the trusses. It further allowed for free space between the trusses to remain open for future blade testing. The three dimensional truss forms would require special joints at the frame corners. We decided early in the project to design and price these joints as steel castings.[13] With eleven frames, some economy of scale could be achieved in the castings, which would ensure a higher level of quality control than welded joints. The castings would also make it possible to transfer approximately 440 kips of vertical force and 330 kips of horizontal force from the roof truss nose pipe to the column truss nose pipe without any visual disturbance to the frames. By allowing these critical joints to disappear, the steel castings helped to create a pure and refined form.

Figure 12 shows schemes for different panel point dimensions.



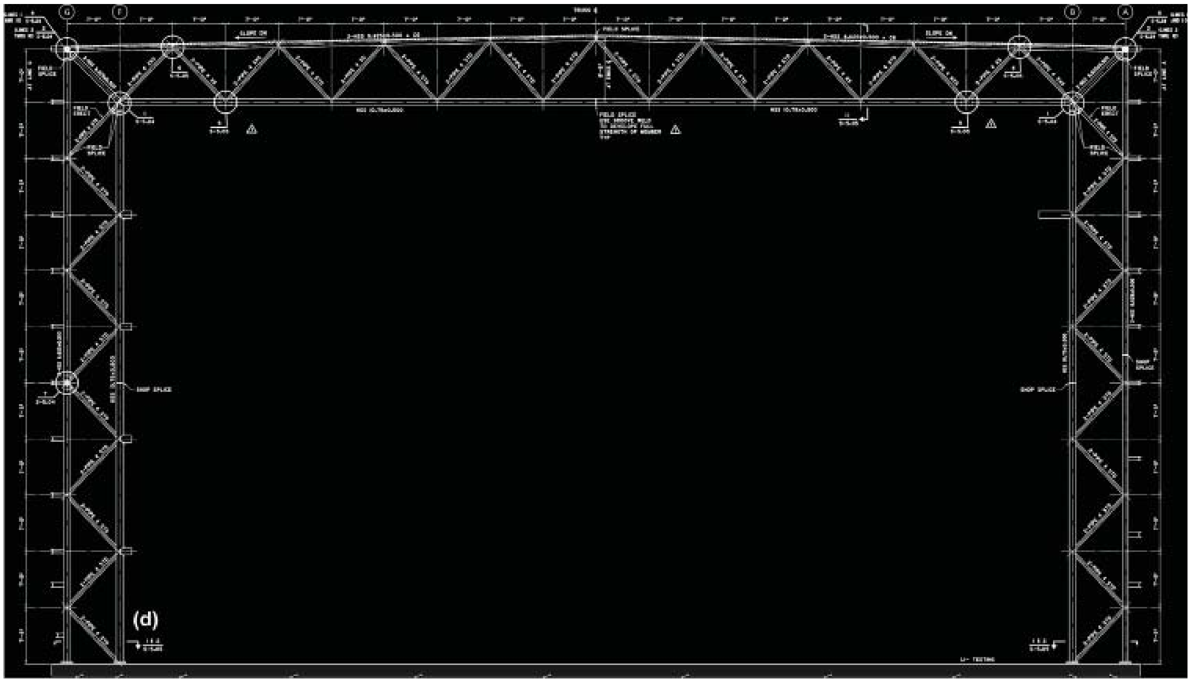
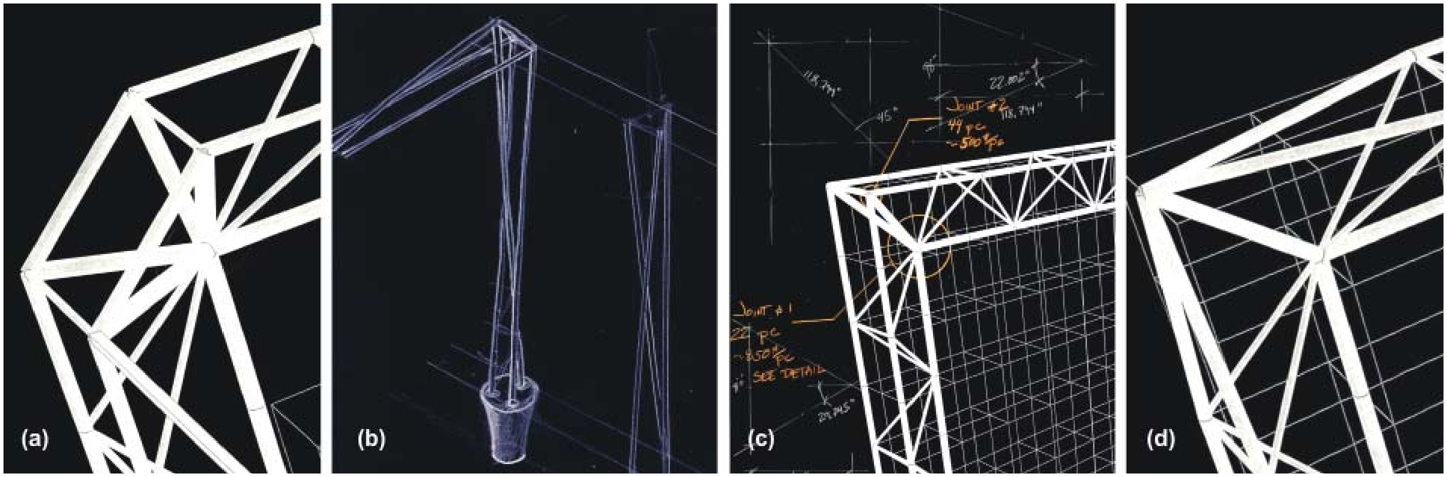


Figure 13

WTTC frame corner details.



We set the panel points in an attempt to harmonize the overall form with its diagonal members. Details in Figures 12(b) and (c) represent multiple studies of the truss panel points to ensure that the diagonals would not intersect. This was important not only for visual reasons, but would also avoid the expense of analyzing, fabricating and welding overlapping diagonals. The object of the panel spacing studies was to reach a height of approximately 80 ft with 7 ft deep trusses and ensure a high degree of regularity in the panels. Figure 12(a) shows a concept for an 8 ft deep roof truss on 7 ft deep column trusses—which resulted in a jarring visual transition between roof and columns. Figure 12(b) shows an attempt to lengthen the panels and emphasize the slenderness of the 4 in. diagonal members in contrast with the more robust chords. Although the transition at the frame corners was not symmetric, it did express some dynamism in the relationship between the diagonals and the chords. The resulting longer diagonal and chord spans would have necessitated larger sizes in the most heavily loaded members, however. Among these studies, it had already been concluded that all diagonal shear members could be used instead of the combination of vertical and diagonal shear members shown in Figure 9(a). The final panel layout settled on ten-14 ft panels for the roof and five-14 ft-10 in. panels for each column. This satisfied dimensional requirements for the building, maintained structurally workable member sizes, preserved harmony between the roof and column trusses, and maintained a smooth transition at the frame corners. For drainage, the roof was required to slope up 1/4 in. per foot toward center span. In order to preserve the continuity of the frame, the bottom chord was kept straight and only the top chord was raked (Figure 12 (d)). The resulting 8 ft-6 in. depth at the roof truss midspan proved critical for both strength and stiffness under the final analysis. The gradual transition between roof truss depth from the columns to the center span also avoided the heavy-handed appearance of schemes similar to Figure 12(a).

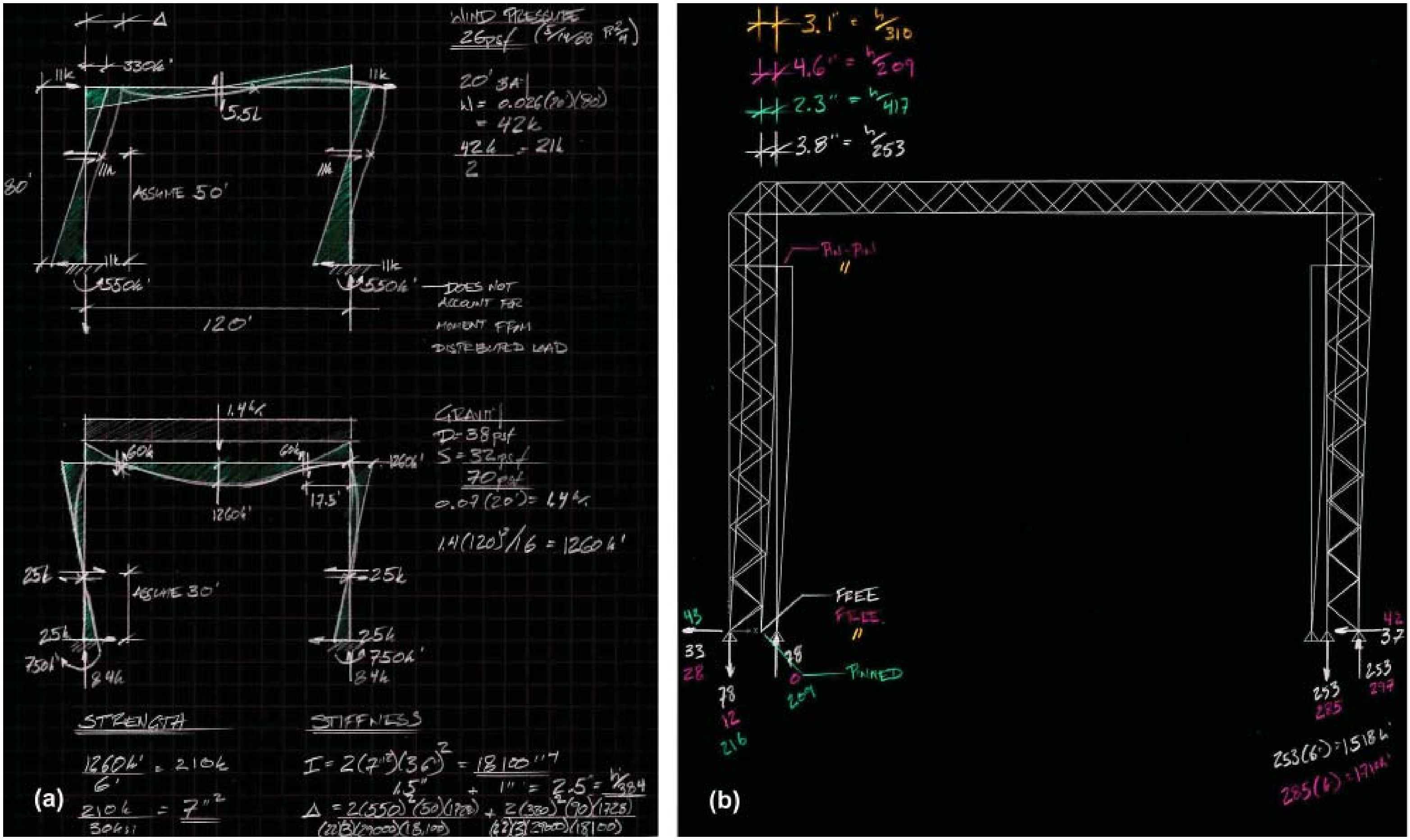
Figure 13(a) shows a study for the frame corners as represented in Figure 12(a) through Figure 12(c). While this scheme had generated interest in profile because of its emphasis on turning the corner and its consistency with architectural proposals to literally curve the corners of the building, it resulted in 10 intersecting members, and seemed to complicate the overall frame. Figure 13(d) shows an attempt to reduce the number of members converging at the nose pipe joint to seven. This scheme also represents an attempt to shape the trusses further in three dimensions. Consideration of construction and appearance, however, led to the judgment that this form was overwrought. Figure 13(b) shows another study of the corner joint with the intention of generating a more radical appearance. The idea behind this form was to follow the moment diagram of the structure under lateral loading. This form resulted in approximately 50% loss of stiffness, however, and again felt unrefined. The final corner scheme is shown in Figure 13(c) as it was communicated to the foundry who had offered to help price the castings. Figure 13(c) shows the two primary cast joints in context along with approximate weights for pricing.

Figure 13(c) also shows the decision to accentuate the corner diagonals by making them the same size as the tail pipes. While these diagonals were required to support higher forces due to joint shear, they could have been made smaller. Similarly, the first two pairs of compression diagonals in the roof span were heavily loaded and required double extra strong sections. Our decision to maintain the larger pipes in the joint region and smaller pipes with thicker walls in the truss span reflected our judgment regarding both the formal and the plastic qualities of the frames. The heavier joint diagonals connect the nose pipe and tail pipe chords visually, while the lighter diagonals inside the spans create a sense of rhythm. The generation of multiple readings from such a simple system was one of the happy results of prioritizing refinement over novelty. This result also speaks to the need for judgment in context regarding structural design impulses such as forming the structure to the moment diagram, seeking maximum three dimensional plasticity, or proportioning all members exactly to their structural demands. Each of these impulses has the potential to lead to elegant results—but not when they are in conflict with larger design drivers. In this case the larger design drivers were the desire for a high degree of lateral stiffness to stabilize the crane, economy of construction, and the pursuit of harmony between the overall system and its parts.

The imagination, expression and judgment of the ideas represented in Figure 12 and Figure 13 came exclusively from the engineers, and are representative of the engineering imagination as it engages structural detail. These considerations of structural detail necessitated that the engineers assume responsibility for connection design in the trusses and for most of the building. Only under these circumstances was it possible to realize the frames as pure forms that could be constructed within the project budget. While our contemporary culture generally works against engineers constructing their own work, it does not exclude engineers from intensively engaging the construction process. The consultant, however, faces challenges in communicating with other team members that needn't concern the master builder. Fortunately, the examples of Robert Maillart in his later career, Fazlur Khan, Bill LeMessurier, Christian Menn and Jörg Schlaich have demonstrated that these challenges can be overcome.

The expression of ideas in Figure 9 through Figure 13 proceeded in the form of drawings, with an emphasis on the visual characteristics of the design. Although some of these drawings suggest systems that are more efficient and economical than others, they all express visual ideas generated by the engineering imagination. The fact that some ideas were judged to be better than others is a natural and necessary part of the creative process. Ultimately only one system would be constructed on this site, and in order to determine the character of this system, it was necessary to review a range of possibilities at different levels of detail. These figures represent only a small portion of the creative process, which consists of unnumbered minute considerations and is impossible to depict in its entirety. The quality of these drawings should be understood in terms of their contribution to the process.

When I encourage my students to draw, I often emphasize that I wish them to draw clearly. Whether they draw well is in many ways beyond the scope of our work together. It is the intellectual part of drawing that matters for the creative process. Here I am referring to drawing in its most general, abstract sense. The hand sketches are drawings, the CADD file in Figure 12 is a drawing, the three dimensional extrusions in Figure 13 are drawings. With the exception of the final CADD drawing, these drawings were



created quickly during a creative process. They were required to be clear enough to facilitate judgments regarding a specific idea. In the act of judging, we were unconcerned with how these drawings came into being. In the act of expressing, our priorities were often speed and clarity. If some drawings were beautiful, this beauty probably resulted from the joy experienced during their creation, or from a deliberate intention to express something beautiful. If some drawings were not beautiful, their inherent beauty may not have been a necessary condition for good judgment. Still, perhaps if other drawings could have been made more beautiful, they might have led to an improved design. These things are difficult to know. The purpose of this discussion, however, is to argue that quality of draftsmanship can and ought to be evaluated separately from the usefulness of drawings in the creative process. The creative process stalls when engineers and students hesitate to draw.

Similar to drawing, a purposeful approach to calculation can enhance the creative process of structural design. Figure 14 shows the results of some analyses engaged during the conceptual design of the braced frames. The final analysis of the frames included models of the entire system with over 128 load cases and consideration of material and geometric nonlinearities. Two separate teams developed independent models and we checked them against one another until we achieved convergence on the most important results. This part of the process is too compli-

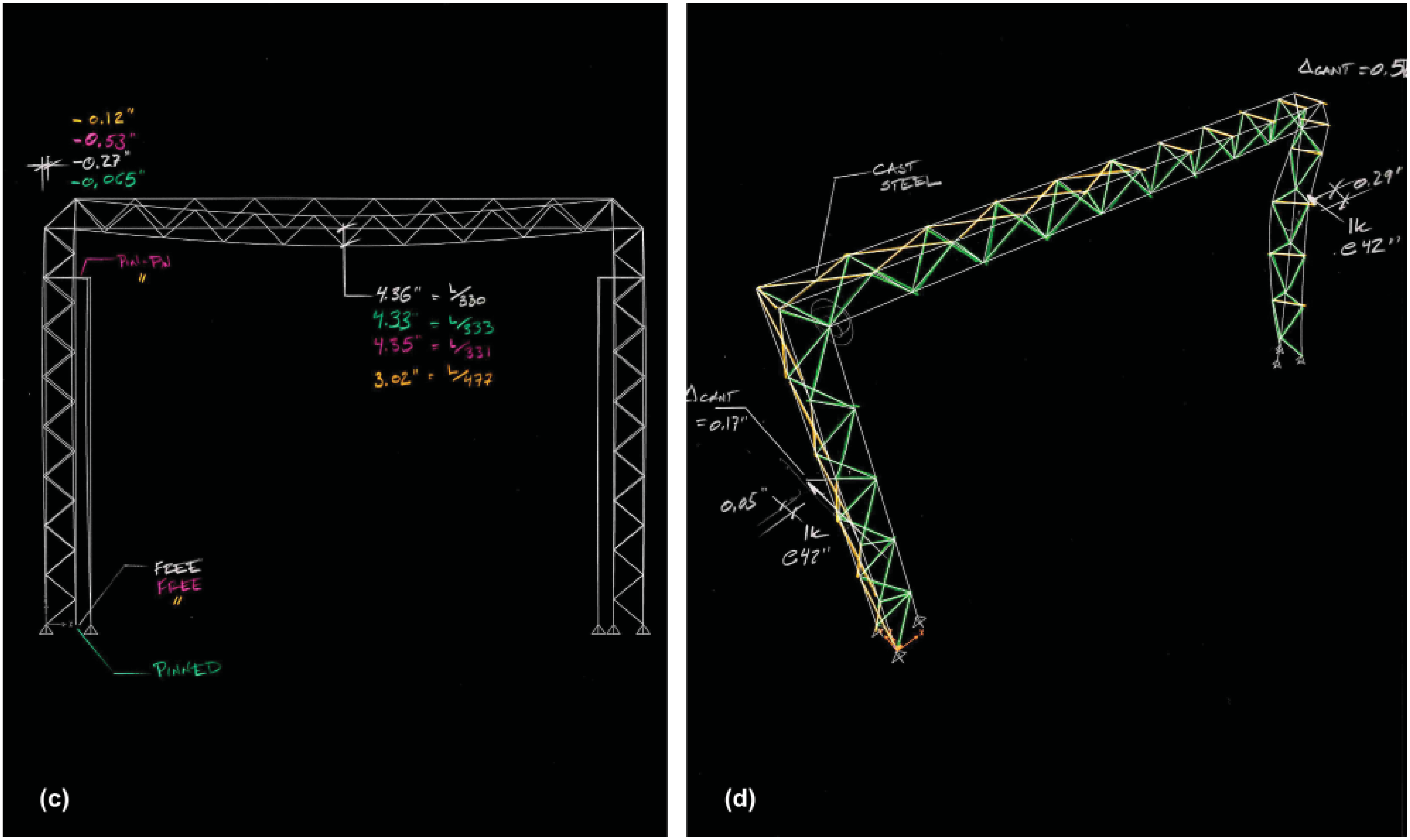


Figure 14

WTTC frame analyses.

cated to represent here. Furthermore, it would add little to this discussion—which is about expressing specific ideas with a level of clarity that allows for sound, defensible judgments. The more complicated part of the process would not be successful had 90% of the important decisions not been made during the conceptual phase discussed here. Note that the conceptual phase emphasized both systems and details.

The images in Figure 14 show another dimension to drawing as the language of the engineer. In these figures, the drawings are rendered to yield analytical insight. Their appearance is in many ways similar to the drawings in previous figures, but the focal points are new. These drawings help to envision deformations and forces. They highlight numerical points of interest and place these key points in context. Again, they are a mixture of hand drawings, calculations and computer output annotated by hand. The mixture of expression by hand and by computer validates the principle discussed earlier—drawings must communicate appropriately. The speed with which they are created, the clarity with which they communicate, and the refinement of their results must be appropriate to the process. For these reasons, they develop organically in an effort to support the imagination and judgment of ideas. As our first introduction to the frames, we produced the analyses in Figure 14(a). These analyses fit onto a single page and became the touchstone by which we evaluated later computer results.

Figure 15

WTTC nosepipe joint.

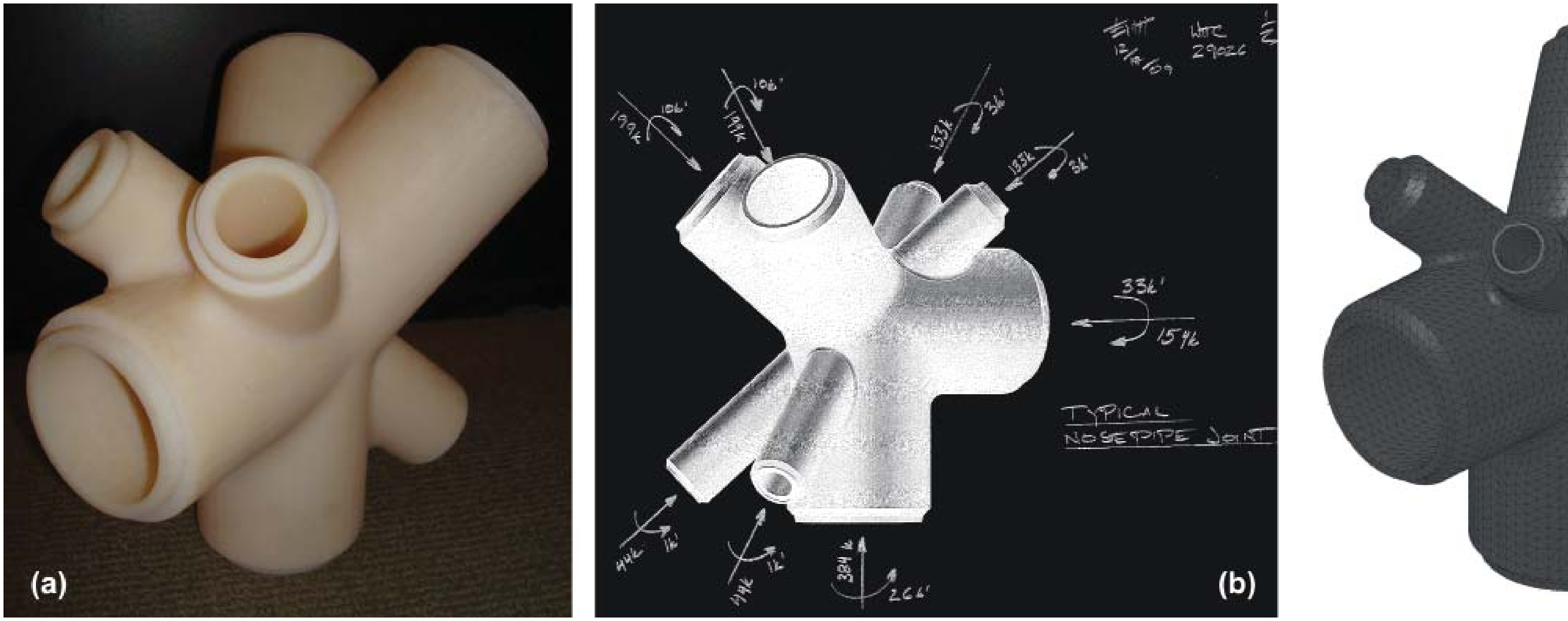
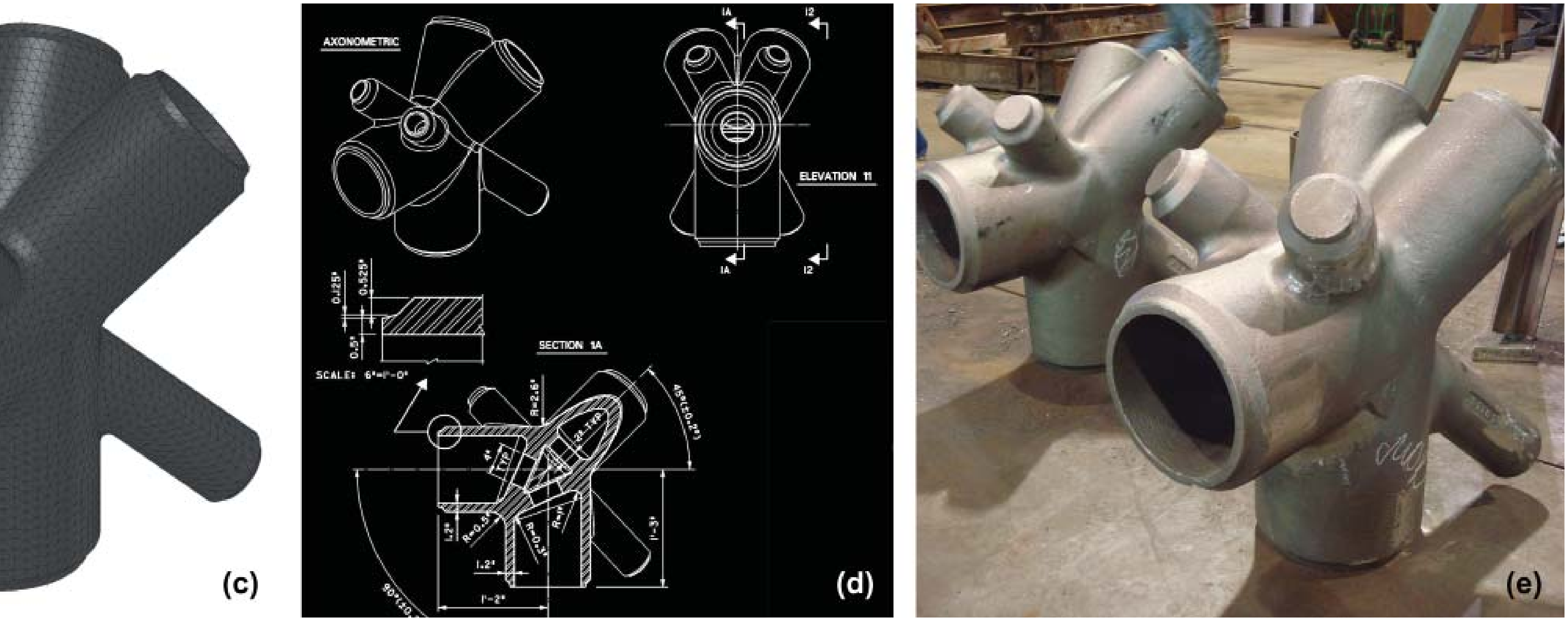


Figure 14(b) and Figure 14(c) represent a series of studies engaged by changing the boundary conditions at the bases of the frames. Rather than print up a new image for each study, the key results were recorded in a color corresponding to that particular study. The colors were kept consistent so they could be recognized at a glance during further discussion. Figure 14(d) shows a three dimensional study of the truss columns' susceptibility to torsional loads. With the exception of the end frames, the trussed frames were allowed to remain torsionally flexible. Removing the diagonals between the tail pipe chords directed visual focus to the diagonals between the nose pipe and tail pipe chords. This was acceptable structurally in all but the end bays, which were required to transfer longitudinal wind loads into the system. Figure 14(d) helped us study the effects of adding diagonals between the tailpipe chords, which ultimately reduced torsional deformations in the end trusses by a factor of six. Because these diagonals were only required in the two end trusses, we were able to construct them symmetrically using cast steel x-joints. The incremental cost of these castings was marginal because there were 42 of them and they constituted a small portion of the total castings order. The consistent principle animating all of the images in Figure 14 is the importance of communication. The communications are made as compact as possible with an aim toward understanding them at a glance. In this way, they can be revisited, shared with colleagues, critiqued and checked.

Perhaps the greatest disappointment resulting from our current use of the computer stems from the reams of data that are printed and submitted as calculations. Without an engineer to make sense out of the data, and to refine this sense into legitimate communication, the analyses themselves are worth little. The virtue of hand calculations in our current age, therefore, is their contribution to sense-making. While I do not wish to state this absolutely, I notice a general correlation between the quality of an engineer's thinking and the balance they maintain between computer results, hand calculations, drawings, notes, tables and figures. Foolish



consistency in this regard can have detrimental effects, but as a rule of thumb, consistent integration between human activity and computer activity seems to benefit the creative process.

Figure 15 shows the nose pipe joint in five different contexts, ranging from a physical model (a), to a finite element model (c), to construction documents (d), to an image of the completed joint (e). This figure shows again the range of purposes that can drive communication about this joint. The figure does not include representations of the multiple iterations required to develop the joint's interior, to carry loads, or to refine the appearance of the fillets. Understood in general terms these five images are five different *drawings* of the joint. In other words, they are not expressed in the languages of words or mathematics. I prefer to call them drawings in order to maintain consistency with Culmann's assertion that "drawing is the language of the engineers." The drawing in Figure 15(b) was sent to the fabricator during a value engineering exercise with the object of redesigning the cast steel joints as weldments. Once the fabricators understood the demands on these joints, they recommended to the general contractor not to pursue this further. This communication was as much a part of the creative process as any other. An idea was imagined by the contractor to redesign the joints. The loads on the joints were expressed, and a judgment was made not to pursue a redesign based on these loads. Interestingly, during this value engineering process, it was critical that the castings survive based on their technical and economic merit alone. Had the engineers expressed any preference for their appearance, they would have categorically been perceived as too expensive. While this experience presents a sad commentary on contemporary American aesthetic culture, it is not inconsistent with the tradition that structural artists often assume full responsibility for the construction of their work. When the structural artist is also the builder, she needn't be concerned with the politics of "value engineering"—a process that typically offers little value and even less engineering.

Figure 16

WTTC trussed frames with nosepipe casting. View looking north during construction. Decking for office slabs can be seen on the north side of the lab.

Figure 16 provides a compelling synthesis of the aesthetic choices discussed in this section. Additional members would have obscured the structural form and detracted from its visual power. The three dimensionality of the trusses makes it possible to experience them as objects as well as spaces. Although the view shown in Figure 16 is not accessible to every laboratory visitor, it is possible to experience similar views from inside the trusses on the laboratory floor. In order to save money on the foundations, laboratory offices were designed inside the north trusses, so it is also possible to experience the trusses and castings on a human scale as well as the scale of the laboratory. The trusses are simple enough that they give way to the laboratory space when they are not the focus, but they are able reappear as interest dictates. As Figure 8 shows, their lightness makes the bridge cranes appear to float above the lab floor. To have ignored the bridge cranes visually would have been to misunderstand the form of the lab. To have competed with them would have distracted from the unity of the space. Even inside this relatively simple system, there were countless choices we were required to make. Some of these choices were judgments based on analysis, but some of them were also judgments based on a conscious desire to express an aesthetic emotion. In such cases, the bases for these judgments were subjective thoughts and feelings. It is possible to have made other choices at multiple levels in the design. While many elements of the design were refined through careful analysis, the design is not an optimum, it is the conscious and unconscious result of an intensive creative process born out of the engineering imagination.

Figure 17

Lobby Renovation, 100 High Street, Boston, Massachusetts.
(left) Before: two levels of retail space at base of 28 story building [CBT Architects]. (right) After: two-story lobby with structural glass wall hung from cantilevered third floor [Edward Jacoby].

Drawing and the Education of Structural Engineers

In order to provide further context for the characteristics of drawing as a language, I will discuss two recent lobby renovations in Boston and their role in my teaching the third year steel design course at Tufts University. Figure 17 shows before and after photos of a lobby renovation completed with CBT Architects at 100 High Street in Boston in the spring of 2009. The former entrance to the building in Figure 17 was located at 150 Federal Street. The lobby renovation consisted of removing three bays of slab framing from the second story in order to create a new 2-story high lobby with a structural glass façade by W&W Glass/Pilkington Planar.[14]

Figure 18 shows the framed area before and after the slab was removed. Since the new glass wall was to be hung from the cantilevered third floor framing, reinforcement of the columns prior to demolition of the slabs required not only considerations of column stability under 28 stories, but also of column flexural deflections and their effect on cantilevered slab deflections.

Figure 19(a) shows original sketches and calculations developed during concept design of this slab removal. While it may seem natural that sketches, calculations and words occupy the same page of work (as do also graphs and tables often times), it is important to note that many students are not educated to communi-

Figure 18

Lobby Renovation, 100 High Street, Boston, Massachusetts.
(left) Before: columns and cantilevered girders reinforced prior to removal of three 30 ft x 30 ft bays. (right) After: three bays of slab framing removed, and column reinforcement completed.

cate in this kind of hybrid language. At the top of Figure 19(a) is a sketch of the plan, which gives context and which will become the primary form of communication in later contract documents. Also listed are the assumed loads. These loads are deliberately simple, and their importance lies in the fact that they allow this communication to stand alone, without reference to other documents. This makes the work easier to check and to discuss with colleagues. For columns supporting a fully-occupied 28-story building, it became important to check both the relevant assumptions and calculations many times, with many different colleagues. The intellectual merit of the problem lay in distilling the problem down to its essence—to make it so simple that the unconscious could continue to consider the problem at all hours—so simple that one could wake up in the middle of the night and check the work at bedside. The analysis on the lower portion of Figure 19(a) is a simple, single degree of freedom moment distribution, which was carried out on half a page. A sketch of the physical system with moment diagrams helped to facilitate this level of conceptual transparency.

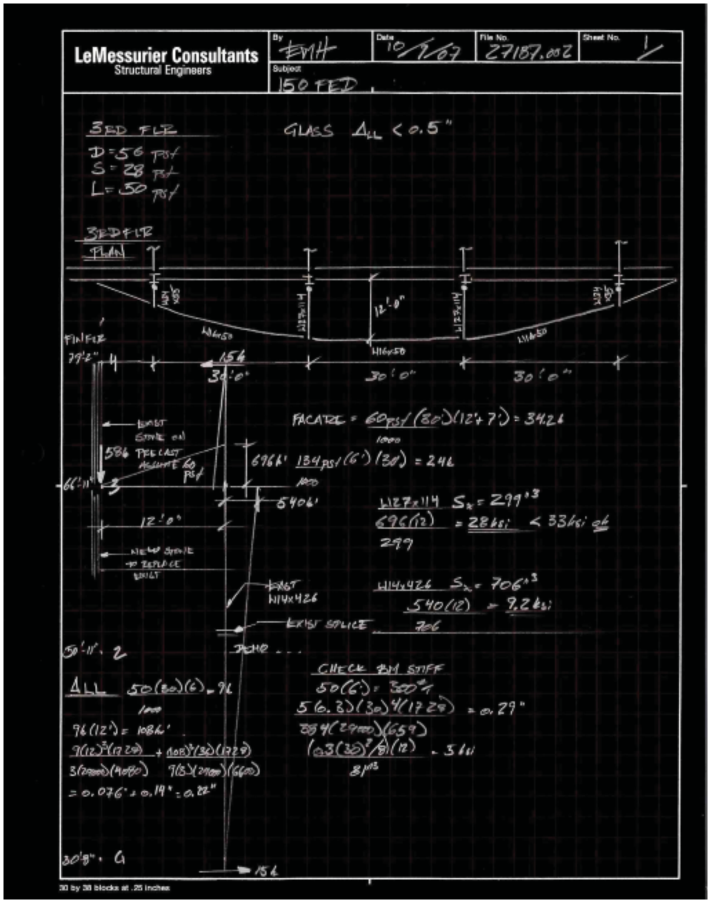
Figure 19(b) shows a series of homework exercises based on a parametric investigation that followed the calculations in Figure 19(a). The object of the investigation was to determine the stiffening effects due to a range of possible reinforcement schemes for the cantilever and its beam and column back-spans. I learned from assigning this series of problems that there was a significant

Figure 19

Lobby Renovation, 100 High Street, Boston, Massachusetts.
(left) Initial analysis of third floor framing to support hung glass wall.
(right) third year structural systems homework assignment reflecting the parametric investigation of system behavior completed prior to final design.

difference between how I saw these simple sketches and how my students and teaching assistants saw them. I saw several variations on one theme—a cantilever with a backspan. The variations entailed different types of backspans resulting in different levels of rotational stiffness at the root of the cantilever. My students, however, saw eight different problems, with little or no conceptual thread running through them.

When I solved these problems in Figure 19(b), the moment diagrams and axial force diagrams yielded significant insight into system behavior—even before I calculated any numbers. From the principle of virtual work, more area under these diagrams implied more system flexibility. To a novice, the diagrams appear more simple than they actually are. This speaks to the subtlety and effectiveness of their abstraction. Only an expert can see all they have to offer. And to an expert, they facilitate a powerful understanding. A similar observation was treated extensively by the National Research Council in *How People Learn*.



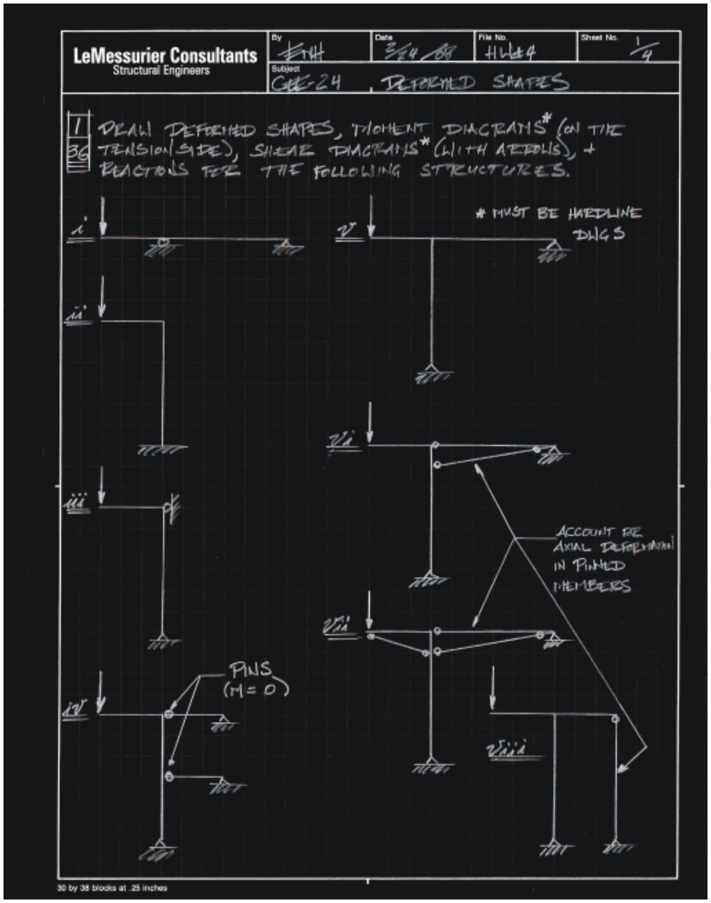


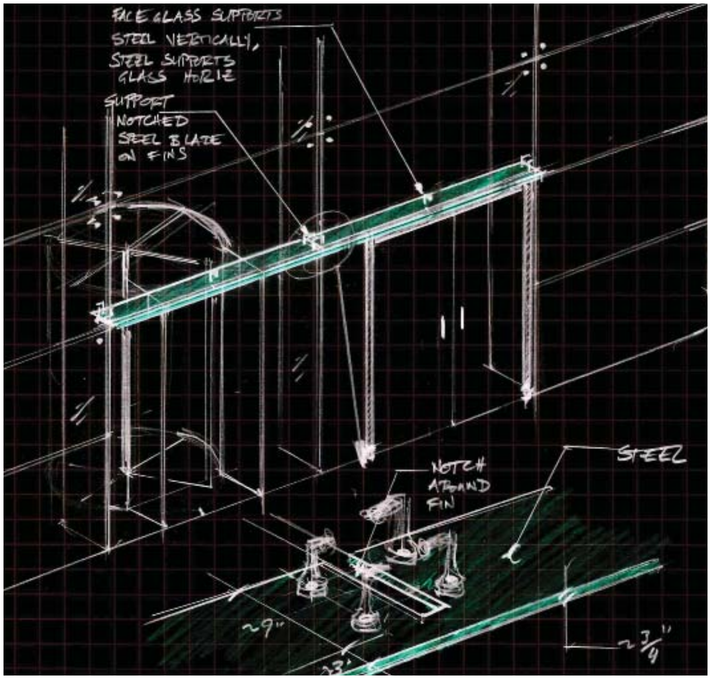
Figure 20

Lobby Renovation, 225 Franklin Street, Boston, Massachusetts. Engineer's sketch of steel reinforcement for glass door header.

> Experts' abilities to reason and solve problems depend on well-organized knowledge that affects what they notice and how they represent problems… The fact that experts are more likely than novices to recognize meaningful patterns of information applies in all domains, whether chess, electronics, mathematics, or classroom teaching… Because of their ability to see patterns of meaningful information, experts begin problem solving at "a higher place."[15]

Figure 20 shows a sketch for another structural lobby renovation at 225 Franklin Street in Boston. I developed this sketch during a coordination meeting with the architect, the glass installer and the general contractor. During the meeting, the sketch helped our team to align our interests with regard to developing an slender steel header that could be attached to the glass system. Both the system and the details were important to all parties involved, and the actual engineered header system ended up resembling this concept sketch closely.

Figure 21 shows an elevation of the 225 Franklin Street entrance, which was conceived as a glass box, protruding from the intensely textured 1963 façade. This façade is supported by floor slabs cantilevered 17 ft from the building columns. The box is transparent, but also ordered in its proportions and arrangement of insulated glass lites. Accentuating this order, the lites have a horizontal orientation, the joints between the lites are filled with black silicone, and the portals assume the exact space of two lites. From outside, the repose of the glass box intensifies the dynamics of the Paonazzo marble wall which presides over the lobby's interior. Once inside, the lobby's horizontal orientation heightens the excitement of approaching the rare marble wall to study its golden and rust colored limonite markings.



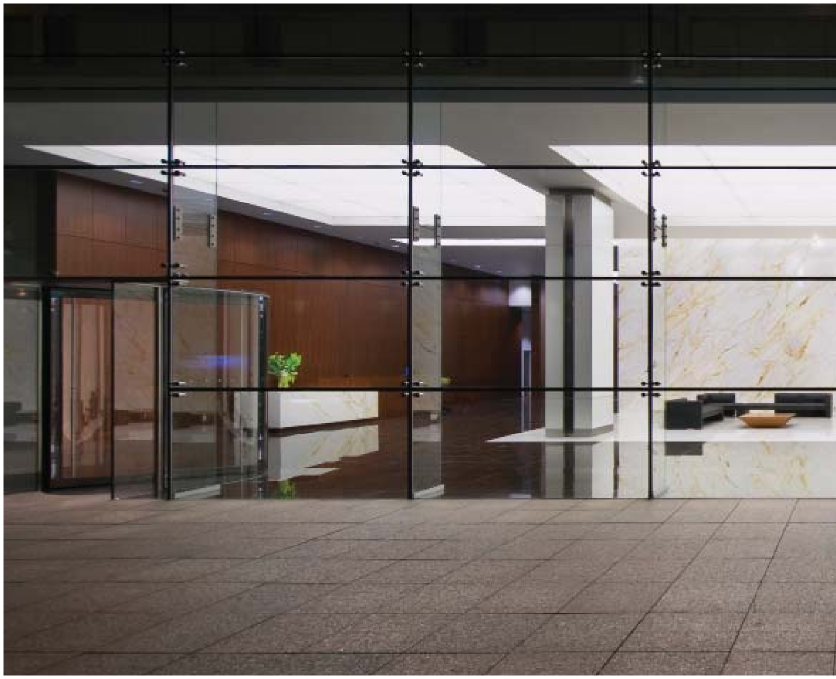
An Abundance of Means

In our current age of advanced technology, why should we even consider executing our calculations and drawings by hand? Current questions regarding the relationship between the computer and hand calculations are reminiscent of the tension between machine production and handicrafts that began over a century and a half ago. Gottfried Semper, who was a colleague of Karl Culmann's, visited the 1851 Crystal Palace Exhibition in London and wrote a famous essay on this tension.[16] Semper wished to remain optimistic about machines that "encroach deeply into the field of human art, putting to shame every human skill," and asserted that "there is no abundance of means but only an inability to master them." By the early 20th century, the question of machine production had come to dominate modern architectural discourse.

Our current use of computers has developed all the more rapidly in light of our hindsight regarding the history of machine production. What seems to be missing, however, is the intensive cultural discussion that flourished from the 1850s to the 1920s, on the merits and weaknesses of the new tools. I can't help but feel that we are missing a cultural opportunity, and perhaps also an economic opportunity, in our reluctance to discuss what it means to have mastered our tools.

The changes are occurring rapidly. Within a span of thirty years, we have transitioned from hand calculations, punch cards, drafting boards and blueprints; to CADD, structural analysis software, and laser printers; to BIM, structural design software, professional outsourcing and electronic files. At the same time, codes have changed nearly every three years and have multiplied in size and number. Our present tools are powerful. They have the potential to make our work more efficient, more accurate, and more comprehensible to owners. So why do we need engineers? What does it mean to have mastered our tools? Since before Semper's time, machines have successfully replaced human labor—even skilled labor. Still, it remains important to sit with these questions. They may be uncomfortable, but to engage them thoughtfully is to chart the future of engineering. I don't intend to answer these questions so much as to offer a personal response to them.

Since the industrial revolution of the 18th century, we have created unprecedented wealth by systematizing, dividing and refining our approach to labor and production. In the service of this grand project, engineering has developed a reputation for acting instrumentally, for rationalizing and optimizing. This reputation, however, misrepresents most of the stories behind the engineering that supports our modern world. What needs to be made transparent is that even design in the everyday professional sense requires a human way of thinking—drawing on experience, analogies, associations and feelings. The interaction of the human and the technical is the life blood of our modern world, but this interaction is hard to understand and discuss. For this very reason, we ought to value this discussion as one of our most



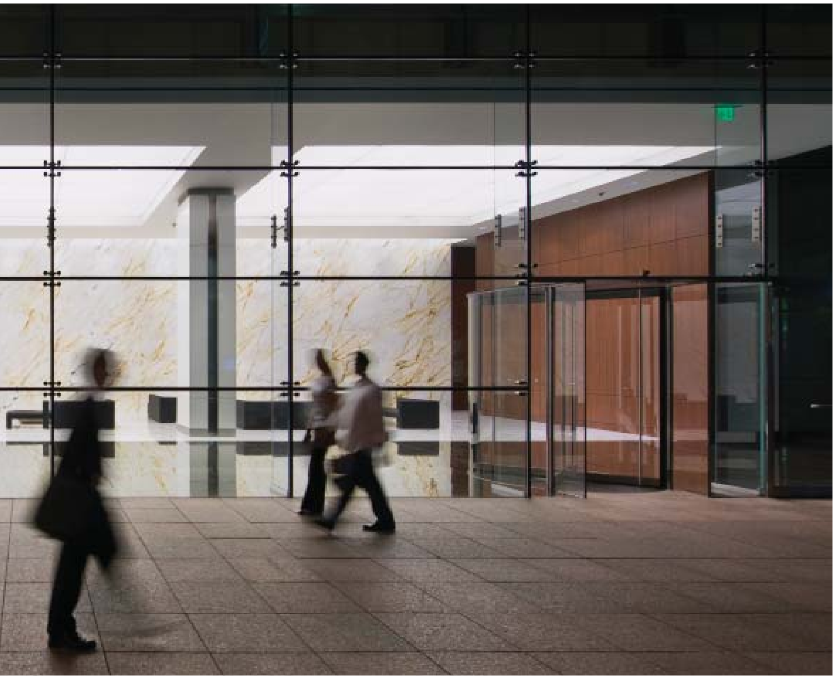
cherished and important intellectual disciplines.

While our trade journals are filled with articles wishing to advertise an ability to keep pace with our latest tools, a few simple observations seem to escape discussion. For instance, building professionals have grown more uncomfortable with drawing by hand. This makes it harder to express and discuss new ideas at meetings. Necessity no longer requires younger engineers to calculate by hand. This has removed the old safeguard that proficiency not attained in school would be acquired in practice.

For the first time in history, it is possible to practice for ten years and not advance beyond fundamental understanding attained as a student. Prior to the widespread use of computers, engineers spent thousands of hours calculating by hand. The imperative to calculate by hand continually challenged engineers to rethink

Figure 21

Lobby Renovation, 225 Franklin Street, Boston, Massachusetts. Front elevation with portals. [photo: Anton Grassl/Esto]



problems, to simplify them, and to understand them fundamentally. With justified excitement and satisfaction, our profession has embraced its liberation from arduous calculations. We have not come to terms, however, with the loss of mental discipline that naturally accompanied them. At its height, the fundamental understanding and mental discipline that made hand calculations possible also supported the calculations behind the Valtschielbach bridge discussed earlier.

Robert Maillart's design of the Valtschielbach bridge teaches us that human judgment, in the service of clear understanding, exceeds in power and majesty even the most complex computations. This is a different way of thinking than either accepting the drudgery of complicated hand calculations or accepting uncritically a computer's "answer" as the truth. I do not disagree with Semper. There is no abundance of means, only an inability to master them. Maillart and the other great structural designers teach us, however, that we master our tools not by learning every new tool that comes along, but by making sense out of their use.

The current abundance of means forces me to ask myself the question: "Is it moral for me not to understand what I am doing as an engineer?" Phrased in this way, most people I have asked would answer the question, "No." But consider how this is complicated. Perhaps Maillart's academic colleagues sensed something immoral about his use of simple calculations. Perhaps Maillart sensed something immoral in his academic colleagues' insistence on added complexity. From a distance, we may conclude that Maillart won the debate because the Valtschielbach bridge is still standing. Nevertheless, analytical complexity continues to seduce scientific research as practice in our modern universities.

Furthermore, what if the Valtschielbach is simply standing by accident? Plenty of buildings are currently standing whose designers do not fully understand their behavior. Fortunately, however, Maillart *did* understand his bridge. We can see this understanding ourselves, because it is not hidden inside reams of data. Maillart's Valtschielbach calculations provide a compelling critique of misplaced analytical complexity, whether by hand or by machine. Our escape from drudgery ought to provide us with more time for understanding. But for many engineers it has simply created a new drudgery even more insipid than lengthy calculations. At least in the midst of the old calculations, engineers were compelled to understand their work if they wanted any answer at all.

Superior computational power has reduced the apparent need to think long and hard about how best to model structures. This has promoted a literal approach to modeling which is highly inefficient and often incorrect. It has also indulged a culture where professionals and students alike are unable to explain their results. In response to questions regarding structural behavior, I have heard the phrase, "Would you like to see my spreadsheet?" No! I would not like to see your spreadsheet. I would like for you explain to me what is going on. Habitual work on the computer has diminished both a sense of scale and the means of expression available to engineers working on paper. This need not be the case. It is possible to use computers appropriately, but this requires conscious deliberation and judgment. In the absence of necessity, we are left alone to discipline our thinking. This requires a strong professional culture, whose values are clearly understood and expressed.

When I calculate, my pages are filled with sketches, notes, tables, equations, numbers and graphs—each is a means of expression appropriate to its purpose. On a daily basis, our office receives calculations for review that are as empty of thought and clear expression as they are voluminous in size. These calculations not only contain mistakes, but the mistakes can be very hard to find. Taking Karl Culmann at his word, I often develop my force diagrams directly on top of a picture of the structure or detail. Drawing, calculation and understanding are connected. It is not enough to understand the concepts internally. An engineer must convey the same understanding to someone else.

An understanding of the creative process allows me to explain my choices of tools. As a practitioner no explanation is required. As an educator, however, my job is to help students make sense of the world, so I struggle to understand why I practice the way I do. Teaching keeps me honest. For each situation, I judge the value of my tools based on three criteria:

1. How quickly and directly can I express the idea?
2. How much does this expression facilitate judgments and inspire further ideas?
3. How well may I expect this expression to communicate?

These criteria are especially helpful in determining appropriate use of the computer. While I belong to a generation of engineers who are proficient with all types of software, I find that many problems can be solved more quickly by hand—especially if I model them in an efficient way. Other problems are solved more quickly by the computer, but their solution offers less fundamental insight. This poverty of insight has a tendency to obstruct both my imagination and my judgment. Still other problems, however, are solved elegantly and quickly on the computer. The best tool for a given situation is not a foregone conclusion. I am responsible to judge which tool best suits my present purpose. To judge well is to have mastered my tools.

The Role of Design in University Engineering Education

The role of design in university engineering education is to *motivate* and *challenge* students' fundamental understanding of the physical world. Design is relevant in the university, not because it prepares students for the working world, but because it motivates and challenges students' understanding of the fundamentals in the best possible way. Design requires a personal way of directing creative thinking toward the solution of an actual problem. It has little use for rote application of equations that a student may or may not understand. Design requires a philosophical approach rooted strongly in the fundamentals of a discipline. Fundamentals are not just theory, but how theory is applied in a context. To separate theory from practice is to ignore context—and hence to forsake what is most human and most wonderful in engineering.

Architecture and the fine arts have developed superior creative processes to engineering. Lacking a self-conscious creative process, engineering has misunderstood its own human principles and has misrepresented itself to the public. The most common example of this is the canonical structural engineering design course—steel design. While the word "design" is captivating, the course itself often consists of learning how to select pre-formed member sizes from a manual based on force calculations. This is not design. This is member selection.

About three years ago I reached a turning point in my teaching. I had become disillusioned, wondering if I was ever going to produce work that could be expressed in textbook problems. Every real problem, no matter how simple, needed some context in order to make sense. Most designs that could be used to illustrate an analytical point could be improved if I was willing to change the analysis. Eventually, I realized that my professional work would remain problematic to the textbook format for the rest of my career. Reality is messy. I decided that it wasn't my work that was flawed so much as it was the textbooks. Textbooks deliver example problems in step-by-step format—and teach students to look for the steps as opposed to thinking for themselves. Textbook problems are nicely typed and give the impression that whoever solved them was a stone cold genius. My point here is that I had to gather up some courage in order to take reality seriously—and it has greatly benefited my teaching.

The question of what an engineer learns in school and what an engineer learns at work is very interesting. Clearly, work exposes people to hundreds of problems. The question is whether these hundreds of problems get integrated into a conceptual framework that sees them as hundreds of variations on a few important themes. When the framework is not intact, it is more likely that these experiences continue literally to appear as hundreds of problems.[17] My professional colleagues' ability to understand diverse problems in terms of a powerful and efficient conceptual structure appears to have been influenced by their educational experience—particularly their professors and their mentors. The frequency with which my senior colleagues relate stories about their own undergraduate years emphasizes the persistent power and meaning of their education. We know from Professor Billington's scholarship, that Wilhelm Ritter's influence on both of his students, Robert Maillart and Othmar Ammann, played a significant role in these designers' careers.

The purpose of design in the university is not to expose students to all the problems they will see in practice. Rather, it is to expose them to a few carefully selected problems that will allow them to see relationships between fundamental understanding and the design of real structures. These relationships are so strong that they cannot be separated into theory and practice without doing violence to reality—which itself is a unity. Not all real-world problems are appropriate for educational purposes. And simple examples which illustrate a theory as well as they reflect reality are rare indeed. It is a wonder, therefore, that the development of high quality examples for teaching is not an intellectual discipline in its own right.

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INNOVATION AND REGULATION
Structural Art and California Dam Safety Legislation 1900-1930

Donald C. Jackson

Figure 1

John S. Eastwood, circa 1918. [Author's Collection]

In no small measure structural art derives from innovation, as the search for new designs and structural forms extends beyond established precedents that can be—sometimes quite literally—seemingly set in stone. While building upon the success and creativity of what came before, structural innovation cannot fall prey to repetitive mimicry or lazy re-workings of past success. Nothing is ever invented whole-cloth, but structural artists as conceived by David Billington seek new ways to conceptualize problems, new ways to use materials, and new ways to formulate solutions.[1]

Innovation in engineering per force necessitates change, change in terms of what has come before and change in what is considered possible. Even within a strictly artistic environment, change can be perceived as dangerous both politically and socially. The status quo is disturbed, raising fears of precarious consequences (e.g. Stravinsky's Rite of Spring and its supposed threat to western civilization when performed as a ballet in 1913).[2] With structural art the stakes can seem especially high, as the threat posed by change assumes a physical dimension. Innovation with structures opens the possibility of unforeseen failure modes (what if the innovation proves ill-advised?) and failure can cause great human suffering and economic loss. To innovate with structures is to entertain risk, or at least risk as perceived by a public possessing little independent means of evaluating or assessing the technical basis of the innovation.

In the world of the late 19th and early 20th centuries, a time when the possibilities of structural art began to flourish, a desire to regulate technology and provide for public safety gained favor.[3] Technological disasters—be they exploding steam boilers, colliding trains, burning theatres, or the sinking of "unsinkable" ships—were something that presumably could be minimized, if not eliminated, by instituting laws to protect the public interest. Regulation was to benefit humankind by guarding against inadequate design which might deviate from standards proven through experience (or justified by scientific and technical analysis) to provide safe performance. But innovation also requires deviation, not in the sense of failing to meet some standard, but certainly in terms of finding new methods and new design forms. So how to reconcile the competing values of (deviant) innovation and (precedent-based) regulation? Herein lays a great technological conundrum, one of relevance to all forms of structural art past, present, or future.

The tension between innovation and regulation is well illustrated in the history of dam design technology, and particularly in what occurred in California in the early years of the 20th century when engineer/structural artist John S. Eastwood (1857-1924) promoted multiple arch dam technology as a new and innovative way to impound large reservoirs.[4] Analysis of Eastwood's career as a hydraulic engineer and a pioneer in California's hydroelectric power industry has appeared elsewhere and his stature as structural artist was explicated in a recent article in Engineering History and Heritage.[5] What is specifically explored in this essay is the way that Eastwood's work as a technological innovator intertwined with progressive notions of protecting society from unsafe technologies. And as part of this exploration, attention is given to the collapse of the St. Francis Dam and the way that this tragic failure (which killed more than 400 people in March 1928) impacted California's dam safety regulation. While the design used at St. Francis bore no connection to the multiple arch technology championed by Eastwood, the ramifications of the St. Francis disaster nonetheless held great import in terms of how Eastwood's approach to dam design fared in the years after his death.

Dams and the Public Interest

Water storage, and the water rights that adhere to those who can successfully impound flood flow, comprises a critical nexus in the political economy of the American West. Storage dams are expensive and the viability of large water projects (whether intended to support irrigation, hydroelectric power generation, urban expansion, etc.) were, as Eastwood well knew, often dependent upon finding ways to reduce capital expenditures. In reducing the amount of concrete required for large dams, Eastwood's multiple arch designs offered a way to significantly reduce construction costs. And in reducing the cost of water storage, Eastwood believed that a great public benefit would be brought to the arid West. Less flood water would flow unused into the ocean or evaporate from desert lake beds. More water could be diverted for irrigation or for power production or to nourish municipal growth. Water storage served the greater public interest and Eastwood extolled this principle in a 1914 speech: "The California slogan 'ere should be, that t'is a crime to let our rivers reach the sea." In his view, any impediment to the proliferation of multiple arch dams—which promised widespread reduction in the cost of water storage—acted counter to the greater public good.

To understand Eastwood's experience as a structural innovator it is important to appreciate that multiple arch technology represented a distinctive approach to dam building, one that stood in stark contrast to those spawning more traditional and more expensive massive gravity designs. From this difference, important questions arose. In pursuing cost-saving innovations in form-making that challenged the massive gravity dam paradigm was Eastwood incurring undue safety risks? And should (or how should) the public be protected from such risks by dam safety regulations? These questions were of particular importance to engineers holding a professional interest in the development and proliferation of massive gravity dam technology. To a structural artist such as Eastwood, dams that minimized concrete quantities while also meeting the mathematical requirements of safe design were a good thing, something that served a broad public good, regardless of how engineers tied to massive gravity dam technology might feel. But we should not be surprised that engineers oriented toward (and invested in) gravity dams might perceive Eastwood's ideas as a threat both to public safety and their economic livelihood. Advocates of massive gravity design were skeptical of Eastwood's supposed innovations and, to protect the public as well as their professional status, they sought ways to block proliferation of multiple arch dams. Who was right? The question is important and not amenable to a simple, easy answer. But a consideration of how Eastwood's ideas fared in the face of state regulation offers insight into how regulatory regimes can act to suppress innovation and, by extension, structural art.

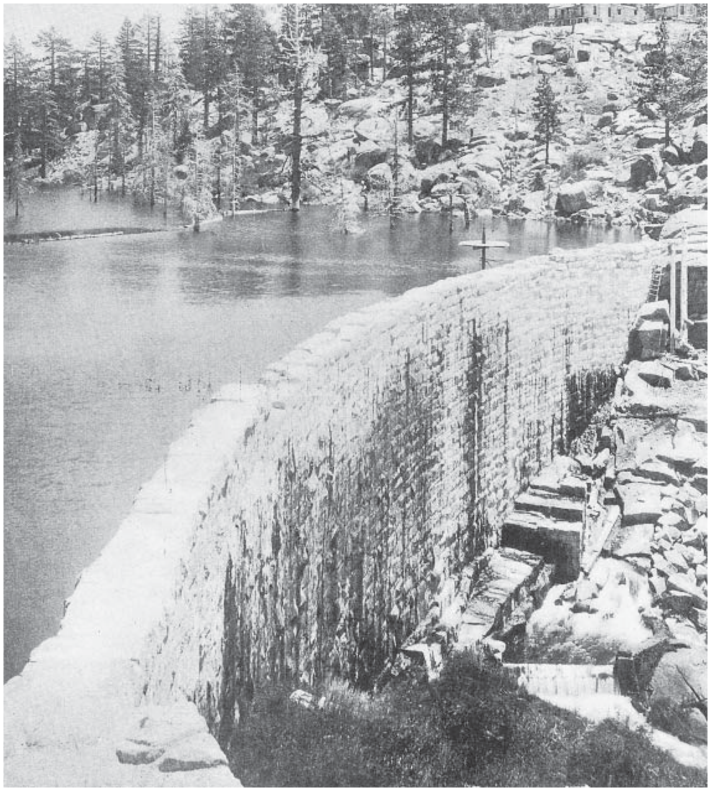
Design Traditions & Disasters

Dam construction dates back thousands of years and breaks down into two basic modes or traditions, only one of which is compatible with the precepts of Structural Art. The Massive Tradition relies upon the assemblage of huge quantities of material (comprised of earth, rock, concrete or combinations thereof) of such mass that the water pressure exerted by a storage reservoir is insufficient to move or dislodge the structure. Massive dams have been built since ancient times and, although they are cer-

Figure 2

Bear Valley Dam in Southern California shortly after completion in 1884. The 64 foot high thin arch design featured a maximum thickness of only 20 feet, allowing for a graceful, daring form that exemplifies the Structural Tradition. [Author's Collection]

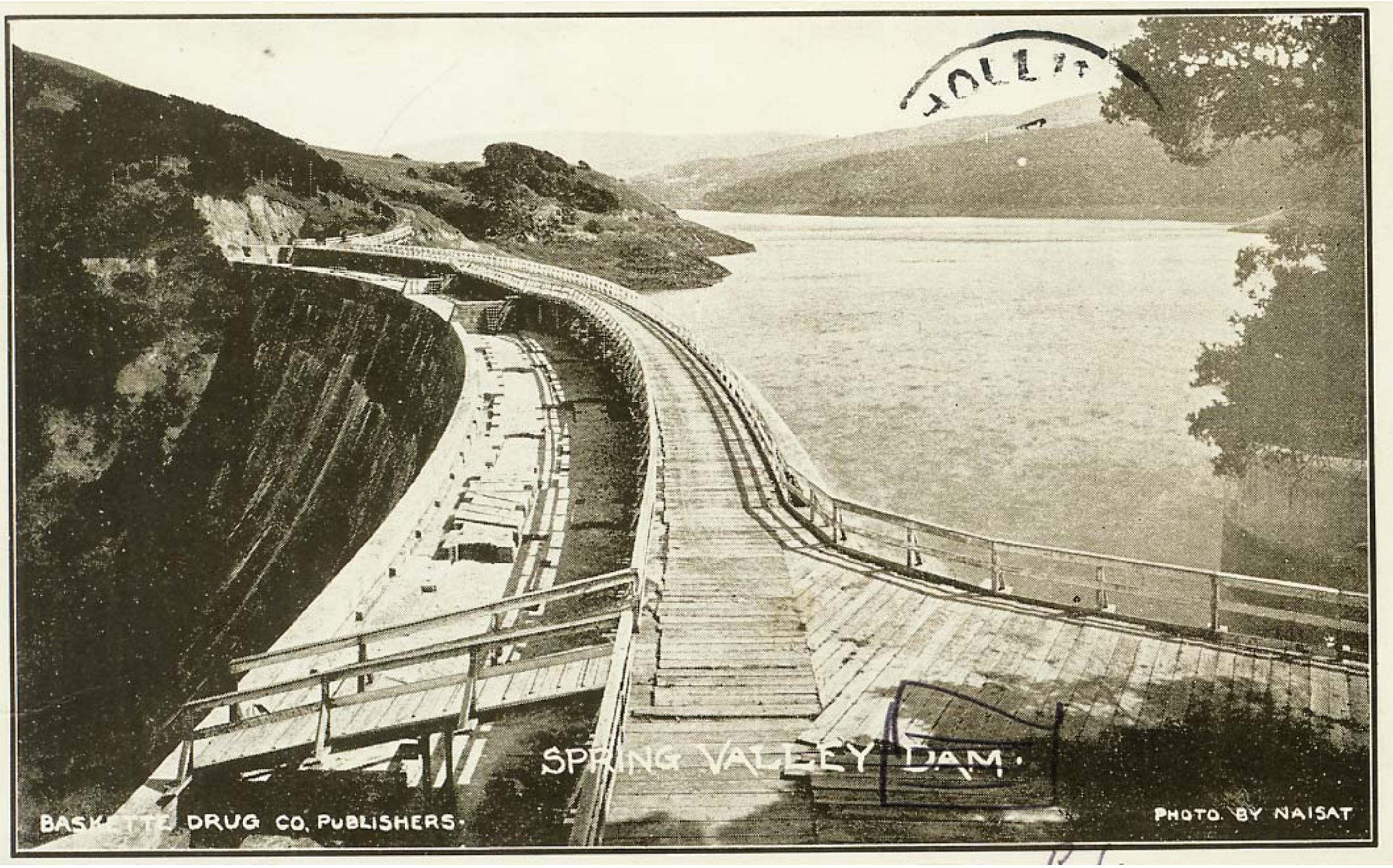
tainly amenable to modern-day structural analysis, at heart they are based upon the simple premise that the more material used in a design the heavier—and hence safer—it will be. In contrast, dams built within the Structural Tradition rely not so much on the weight (or mass) of material in the design but rather on the form (or shape) of the structure resisting the hydrostatic forces. Dams in the Structural Tradition are naturally aligned with the precepts of structural art and fall into two basic categories: 1) thin arch structures in which the cross-sectional profile is too thin to successfully act as a massive gravity dam (i.e. the arch shape is necessary to carry hydrostatic forces to the abutments and provide stability); and 2) buttress dams which rely upon a relatively thin face to hold back a reservoir and a series of discrete buttresses to support the face and transmit hydrostatic forces to the foundation. With less need for materials, construction costs for dam built in the Structural Tradition can drop, often dramatically. This was certainly the case with multiple arch dams; for example, the one Eastwood design that publicly competed against a massive concrete gravity design—and the competing bids were entered into the public record—undercut the lowest gravity design bid by almost 40%.[6]



By the time John Eastwood focused his energies on impounding large-scale reservoirs in the early 20th century, dam building in California had already proven its cultural and economic importance. Spanish/Mexican colonists built small irrigation dams in the late 18th century, but the major impetus for large-scale reservoirs came once gold was discovered east of Sacramento in the late 1840s. Alluvial gold-mining depends upon water to separate gold flecks and nuggets from worthless rock detritus, spurring intense interest in water control technology.[7] By the 1870s some of the highest dams in the world were storing water in the Sierra Nevada and feeding into hydraulic mining flumes; soon after, large dams were also supporting irrigation and municipal development. Some of these structures, such as the rockfill Bowman Dam built by the North Bloomfield Mining Company and the concrete gravity San Mateo Dam built by the Spring Valley Water Company to supply San Francisco with a domestic water supply, adhered to the Massive Tradition.[8] But others, most notably the 1884 Bear Valley Dam built by irrigation interests in San Bernardino/Redlands and the 1888 Sweetwater Dam south of San Diego were among the most prominent—and daring—thin arch masonry dams in the world.[9] When Eastwood started building his first reinforced concrete multiple arch dams in 1908, he operated in a regional environment where the Structural Tradition had already found expression. But more than a few massive dams were also in use in California, setting the stage for a confrontation between Eastwood and advocates of the Massive Tradition. A key issue underlying this impending confrontation involved safety and a desire to protect the public from horrific disasters.

Figure 3

Crystal Spring/San Mateo Dam south of San Francisco soon after completion in 1888 (sometimes called Spring Valley Dam because it was built by the Spring Valley Water Company). As initially built, this curved concrete gravity dam had a height of 146 feet and a maximum thickness of 170 feet. The design may feature an upstream arch, but this curvature is not necessary to insure stability; it is an excellent example of a dam adhering to the Massive Tradition. [Author's collection]



So long as dams were relatively small diversion structures their failure, while certainly onerous, did not result in widespread death and property loss. But as dams grew larger (and were intended to store and not merely divert water) they posed ever greater dangers to downstream communities. In the latter 19th century a few dramatic dam failures attracted national attention and brought the issue of dam safety regulation into the realm of public concern. On a Saturday morning in May 1874 the 43 foot high earth embankment Williamsburg Dam west of Northampton, MA suddenly collapsed, releasing 600 million gallons of water into the upper Mill River watershed; within an hour more than 130 people lay dead.[10] Fifteen years later on May 31, 1889 the earth embankment South Fork Dam in western Pennsylvania failed by overtopping, unleashing a reservoir of 4.8 billion gallons. Over 2,000 people died as the ensuing flood hit the unsuspecting city of Johnstown.[11] The Williamsburg and Johnstown Floods were not the only disasters wrought by dam failures but—especially in the case of Johnstown which stands as the worst dam disaster in American history—

Figure 4

Devastation brought by the Johnstown Flood, May 31, 1889. Over 2,000 people died after the collapse of the South Fork Dam; the power of the deluge is evident in the uprooted tree that impaled the John Schulze house. After the flood, this image (along with many more) was widely distributed to a horrified public. [Author's collection]

they galvanized public attention in highlighting the horrors that could result from poorly designed, poorly built, or poorly operated dams. In Progressive Era thinking, it became an article of faith that the existence of dangerous dams could be ameliorated, and hopefully eliminated, by instituting dam safety laws and state regulation.

The remainder of this essay examines the relationship of innovation in dam design and state regulation through a lens focused on Eastwood's work and the opposition he encountered in promoting multiple arch technology. Of equal importance, it also considers the ways that politics affected dam safety in California, and how failure of the St. Francis Dam in 1928 influenced both revision of the state's 1917 dam safety law and enforcement of the new legislation. From this analysis, it becomes evident that dams designed within the Structural and Massive traditions can differ significantly in their assessment by the regulatory state. No simplistic argument is made conjoining regulation with the necessary suppression of innovative engineering. Nonetheless, state regulation of dams can—and did—have an impact on what is considered to be acceptable innovation and political considerations are not always divorced from how dams are evaluated.

Eastwood's Early Dams and John R. Freeman

Born in Minnesota in 1857 and schooled in engineering at the University of Minnesota, John S. Eastwood came to California in 1883.[12] Settling in Fresno, he undertook a variety of surveying and engineering jobs before becoming Chief Engineer of the San Joaquin Electric Company in 1893. Through his work in hydroelectric power he became focused on minimizing construction costs for large-scale storage dams and he first conceived of a cost-saving multiple arch design while working for the Pacific Light and Power Company in 1905-06. The PL&P's corporate management expressed little interest in his innovation (later, the Boston-based firm Stone & Webster built massive concrete gravity dams in place of Eastwood's proposed designs for the company) and he subsequently left the PL&P in search of other patrons willing to support multiple arch technology.[13]

In early 1908 the Hume-Bennett Lumber Company engaged his services to design and build a 64-foot high logging dam high in the Sierra Nevada east of Fresno. In opting to finance the Hume Lake Dam, built in 1908-09, the company relied upon an outside review of Eastwood's design (by an engineer located near company headquarters in Muskegon, MI) and upon the arguments presented by Eastwood regarding the efficacy of the multiple arch buttress design. No state regulation or authority was brought to bear in either reviewing or approving Eastwood's first multiple arch dam. The Hume-Bennett company's support of Eastwood's design represented an internal corporate action that implicitly weighed the risk presented by the proposed dam against the cost savings it promised vis a vis a comparable massive rockfill embankment or concrete gravity design.[14]

Eastwood's second dam, the 93 foot high Big Bear Valley Dam in southern California 1910-11, followed the pattern of Hume Lake

Figure 5

Hume Lake Dam and reservoir, 1910. Built for the Hume-Bennett Lumber Company in the Sierra Nevada east of Fresno, it comprised Eastwood's first multiple arch dam and required no approval by state authorities. [Author's collection]

Figure 6

Hume Lake Dam showing buttresses at east end. The thirteen arches have spans of 50 feet and a maximum thickness of 2.5 feet; the entire structure required 2,207 cubic yards of concrete. Photo taken in the 1982, after 70 years of service at an altitude more than 5,000 feet above sea level. [Library of Congress]

Figure 7

Big Bear Valley Dam shortly after completion in 1911. Eastwood did not simply repeat what he had done at Hume Lake, but developed a different multiple arch design for the 92 foot high structure. The arches feature 32 foot spans and "strut-tie beams" running the length of the dam provide lateral support for the buttresses. 4,684 cubic yards of concrete were needed to complete the structure. [Author's Collection]

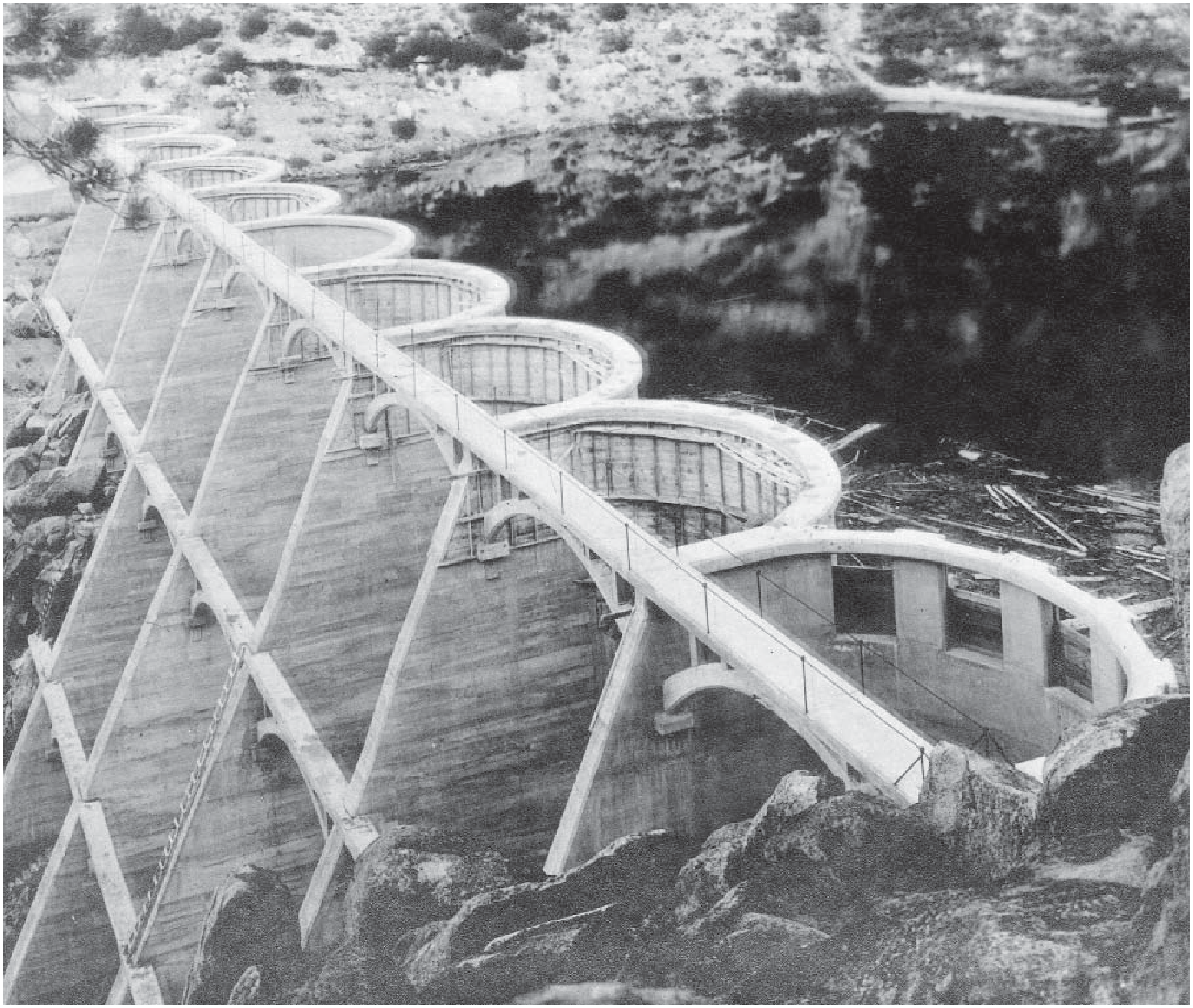


Figure 8

Detail view of strut-tie beam at Big Bear Valley. This type of highly articulated design was later criticized by John R. Freeman as presenting a "lace curtain" appearance that failed to provide the supposed "psychological" assurance offered by massive gravity dams. [Author's Collection]

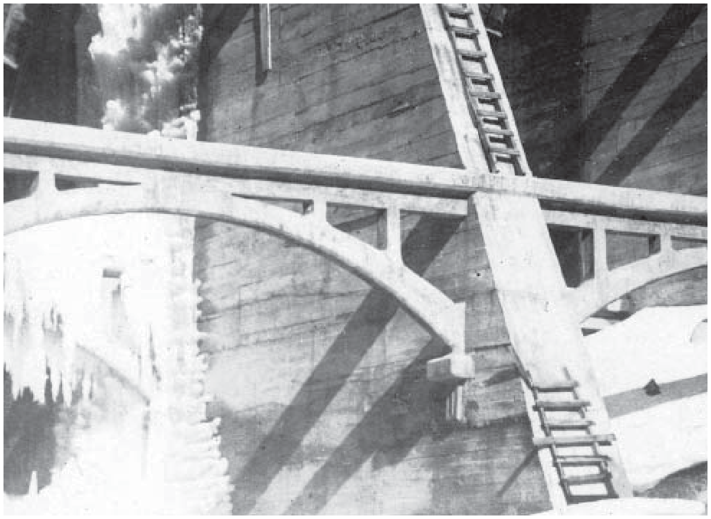
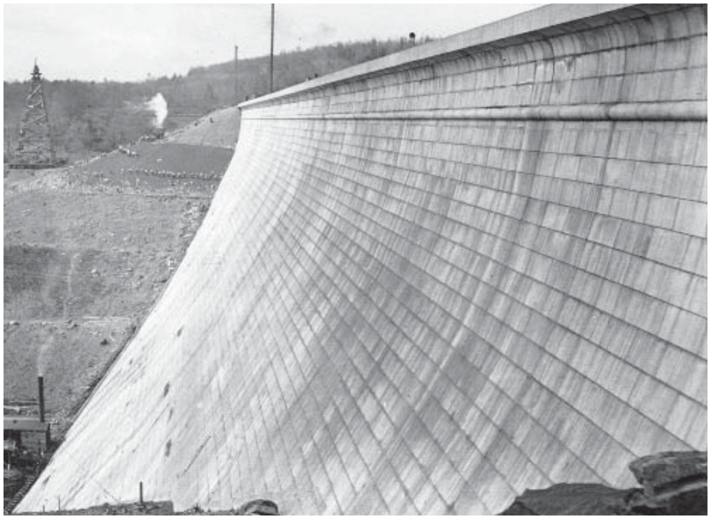


Figure 9

The visually imposing downstream side of Ashokan Dam, circa 1915. John Freeman served as consulting engineer for New York City's Catskill Aqueduct and the system's massive Ashokan Dam (sometimes called Olive Bridge Dam) reflected his notion of what constituted an ideal water storage structure. [Author's Collection]



Dam in that no state regulation influenced or impeded the design/construction process. Eastwood contracted directly with the Bear Valley Mutual Water Company to both design and build the dam; in making its decision to engage Eastwood's services the water company relied upon the counsel of outside engineers to review his plans—but the decision to proceed was entirely at the discretion of the company's leadership.[15]

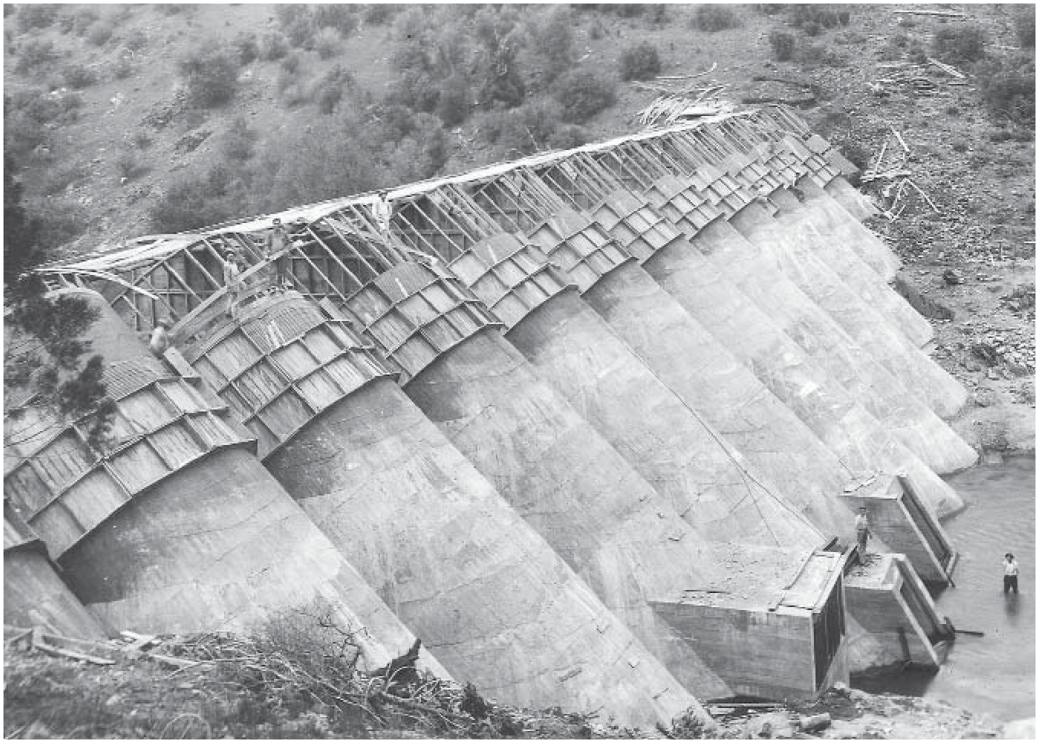
Eastwood's third dam, a 150 foot high structure at Big Meadows across the North Fork of the Feather River in northern California, was similar to Hume Lake and Big Bear in that a privately financed enterprise (in this case the Great Western Power Company) was responsible for the project. While evaluating Eastwood's proposed design in 1911, the GWPC's corporate leadership solicited advice from outside consulting engineers before going forward. Another engineer previously involved with the company believed he was better suited than Eastwood for the dam design commission and, although he was not immediately engaged to review Eastwood's plans, his presence infused the project with far greater complexity than the Hume Lake and Big Bear commissions. This complexity became especially apparent after the GWPC president died in early 1912 (just as Eastwood was starting work on the project) and the in-coming president held no great stake in commitments made by his predecessor.

The aggrieved engineer was John R. Freeman, a prominent New England-based engineer who was a past President of the ASME, a past Vice President of the ASCE, and, among other positions, consulting engineer for the City of New York's Catskill Aqueduct then under construction.[16] Freeman unfailingly advocated massive gravity dams designs as best suited for major projects and, after the new corporate leadership formally engaged his services in the summer of 1912 to review Eastwood's Big Meadows plans, he used the opportunity to attack the multiple arch design.[17] Most notably, he castigated the Eastwood's plans on "psychological" grounds because the supposedly frail "lace curtain" appearance of the multiple arch dam's buttresses would not—at least in his opinion--inspire public confidence.[18] Technical analysis was not something of particular interest to Freeman, as he stressed to the company's leaders that:

> "plainly it is worthy of some considerable expendi-

Figure 10

After being forced to abandon work at Big Meadows, Eastwood carried on with a design for the 60 foot high Los Verjels Dam east of Marysville. Built for a small irrigation company and approved by the California Railroad Commission, the 350 foot long structure featured 20 foot span arches with a minimum thickness of 6 inches; in total the structure required 1,364 cubic yards of concrete. This view shows the upstream side shortly before completion in 1914. [Author's Collection]



ture beyond that necessary to satisfy engineers… in order to satisfy the more or less ignorant public… [who will] regard the dam not from a technical standpoint, but by comparison with the familiar type of solid gravity dam of masonry or earth."[19]

In the end, the Great Western corporate leadership endorsed Freeman's entreaties by abandoning Eastwood's design (after much time and money had been spent on its construction). This decision, however distasteful to Eastwood, largely reflected a choice made by the leadership to pursue one engineer's design over another (a massive earthfill embankment favored by Freeman replaced the multiple arch structure). But the dynamics of this choice was made more complicated because of a state regulatory agency created in 1911 to help insure that corporations acted in the public interest. Known originally as the California Railroad Commission (now the Public Utility Commission), this agency held power over the rates charged by electric power companies and—although it was uncertain at first exactly how far this authority stretched—over the suitability of structures and facilities that ratepayers should reasonably be expected to pay for. Prior to Freeman's efforts in the late summer and fall of 1912 to denigrate Eastwood's Big Meadows design, the Railroad Commission had exhibited little interest in the dam project. But Freeman made a point of bringing his objections to the attention of the Railroad Commission. Subsequently the GWPC's corporate leadership became concerned about questions that the commission might raise about the project. In the end, the company officially chose to abandon Eastwood's design on its own initiative, but in early 1913 the Railroad Commission's hydraulic engineer had echoed Freeman in averring that "gravity types of dams… [comprised] the safest and most lasting form of structure."[20] Later, the commission acknowledged that they had encouraged the company to "change the type of structure" prior to approving an application for a massive earth embankment dam at Big Meadows.[21]

From 1913 onward the Railroad Commission, acting through its Hydraulic Division, came to exercise significant supervisory authority over California dam projects undertaken by the corporations it regulated. As it turned out, over the next decade the

Figure 11

Murray Dam east of San Diego, circa 1918. Built under the supervisory authority of the California Railroad Commission, this 117 foot high, 990 foot long structure reveals how Eastwood had not forsaken his "lace curtain" designs simply because of Freeman's criticism. The Murray Dam featured 30 foot span arches with a minimum thickness of 9 inches; overall it required about 8,220 cubic yards of concrete. [Author's Collection]

Hydraulic Division of the Railroad Commission actually proved to be quite supportive of Eastwood's work once a new hydraulic engineer was appointed in the latter part of 1913.[22] Eastwood's fourth dam, the 60 foot high, 330 foot long Los Verjels Dam built for the Los Verjels Land and Water Company north of Sacramento in 1913/14, was readily approved and supported by the commission. The relatively small structure (at least in comparison to Big Meadows) featured arches with a minimum thickness of only six inches[23] In early 1917 the commission also endorsed and supported construction of his 117 foot high, 900 foot long Murray Dam east of downtown San Diego. Financed by the Cuyamaca Water Company, this design featured arches with a minimum thickness of nine inches and "lace curtain" buttress bracing similar to Big Bear.[24] Based upon the green-light given for the Los Verjels and Murray projects, there was nothing inherent in the process of regulation that required the Railroad Commission to be critical or unsupportive of Eastwood's work. But, as evidenced by the Big Meadows project, state regulation offered a way to suppress design innovation if it fell beyond the bounds of what the prevailing bureaucracy deemed acceptable.

In the first years of Eastwood's work as a dam designer his efforts bore fruit within an economic environment that was, at least prior to the latter stages of Big Meadows, largely unaffected by state-sponsored regulation. Similarly, disinterest (or outright opposition) to his ideas was not specifically related to state authority but was instead energized by other factors. Most significantly, John Freeman vigorously opposed Eastwood's multiple arch designs on grounds that they were "psychologically" inferior to massive gravity dams and represented unneeded experimentation in a field where the price exacted by failure could be so high. In Freeman's view, massive gravity dams provided the public with a visual reassurance of safety that Eastwood's multiple arch designs could never match, no matter what technical arguments might be made in their defense. In contrast, Eastwood viewed Freeman's psychological objections to be "idiotic" and complained to the Railroad Commission that "if all things were to be condemned because they were new, there could be no advancement."[25]

Viewed more broadly, the conflict between Eastwood and Freeman represented essential differences separating the Structural and Massive Traditions of dam design. If someone adopted Freeman's perspective and viewed dam technology through a prism that privileged massive designs—essentially setting them as the standard against which all other designs should be compared—s/he would likely never think highly of a multiple arch design. In terms of regulation, the key question became: Would state agencies charged with responsibility over dams consider designs within the two traditions as possessing equal validity? Or, phrased another way, would the Massive Tradition come to represent a standard that dams within the Structural Tradition (particularly multiple arch dams) would, almost by definition, fall short of meeting?

California's 1917 Dam Safety Law

In January 1916 the earth embankment Otay Dam south of San Diego overtopped and failed during a torrential rainstorm. Fortunately the dam was located at a low elevation close to the Pacific Ocean and, with no major settlements lying downstream, damage caused by the collapse was relatively small. Nonetheless, the failure gave impetus to broad-based dam safety legislation covering water development in the state. A year later, California enacted a new law requiring the California State Engineer to review and approve all non-federal dams over 10 feet high unless they were to be built:

A. By a corporation under the jurisdiction of the State Railroad Commission;

B. Under the supervision of the California Debris Commission (a government agency focussed on regulating hydraulic mining); or

C. By a municipality with a department of engineering.[26]

From an historical perspective the latter "municipal exemption" is most intriguing because it established a special category of dams in California lying outside of any federal or state regulatory regime. The municipal exemption is also of special interest because it did not come about by chance or mere happenstance. It resulted from political lobbying by large municipalities seeking to avoid state interference. This is made clear an October 1928 letter from San Francisco's City Engineer Michael M. O'Shaughnessy to State Engineer Edward Hyatt explaining why, a decade earlier, he had sought freedom from state regulation when building San Francisco's Hetch Hetchy water supply system:

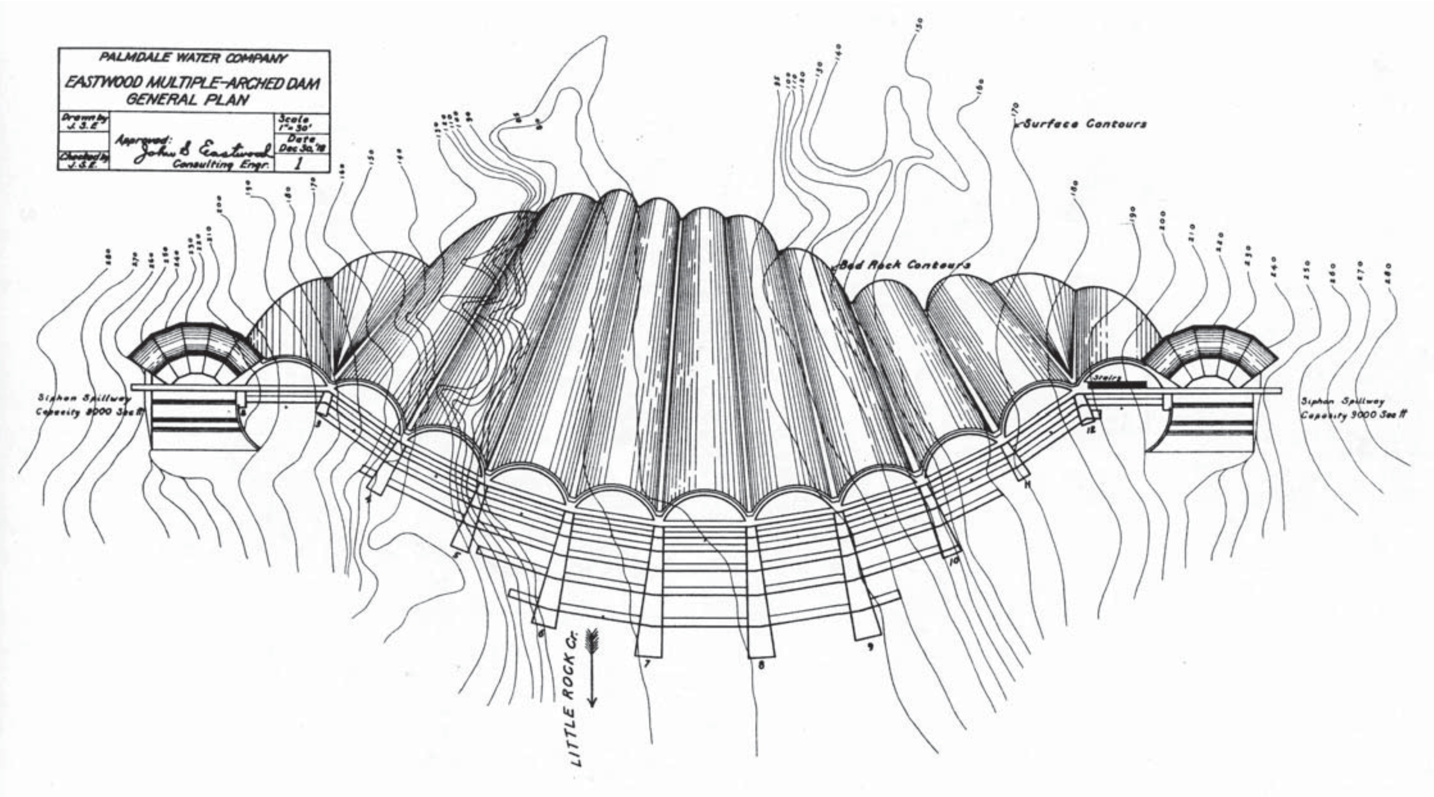
> "I had our City Attorney present objections to the State legislative body in Sacramento in 1917, against allowing [then State Engineer Wilbur] McClure to have anything to do with our dams at Hetch Hetchy, as I did not think, from his previous experience and knowledge, he had the requisite experience to pass on such a subject and I did not care to be subject to his capricious rulings… I did not think that Mr. McClure's previous clerical and engineering experience entitled him to be czar over the plans for our dam."[27]

Eastwood lacked the clout and political influence of someone like O'Shaughnessy, and the new law meant that—unless he was commissioned by a large municipality or a federal agency —any future dam designs for California water projects would be subject to some form of state regulation. As it turned out, the Hydraulic Division of the Railroad Commission continued to be favorably disposed to the innovative character of his work. For example, the Webber Creek Dam built for the Eldorado Water Company near Placerville featured an innovative triple arch design that, by eliminating the use of extensive formwork, significantly reduced construction costs. This 90 foot high dam, which featured a maximum arch thickness of only 12 feet, was built under the authority of the Railroad Commission.[28] But for dam designs coming under the authority of the State Engineer, Eastwood experienced scant support.

Eastwood's troubles with the States Engineers' office are best illustrated by the protracted bureaucratic battle that ensued over his 175 foot high Littlerock Dam in northern Los Angeles County.[29] In late 1917 the Littlerock Creek and Palmdale Irrigation Districts commissioned Eastwood to design a large multiple arch dam to store the floodwaters of Littlerock Creek. At first, everything seemed on track with a design featuring a minimum arch thickness of 12 inches. Then, in the fall of 1918, State Engineer Wilbur McClure unilaterally informed the districts that he would approve

Figure 12

"Radial Plan" design for Littlerock Dam proposed in late 1918. Each arch featured a variable radius (decreasing at lower depths), allowing for thinner, conic arches while keeping a constant allowable stress. To critics, the dam appeared to be arched in the wrong direction (downstream not upstream) and the State Engineer refused to approve the design's "details." Eastwood was unable to build any radial plan designs prior to his death in August 1924. [Author's Collection]

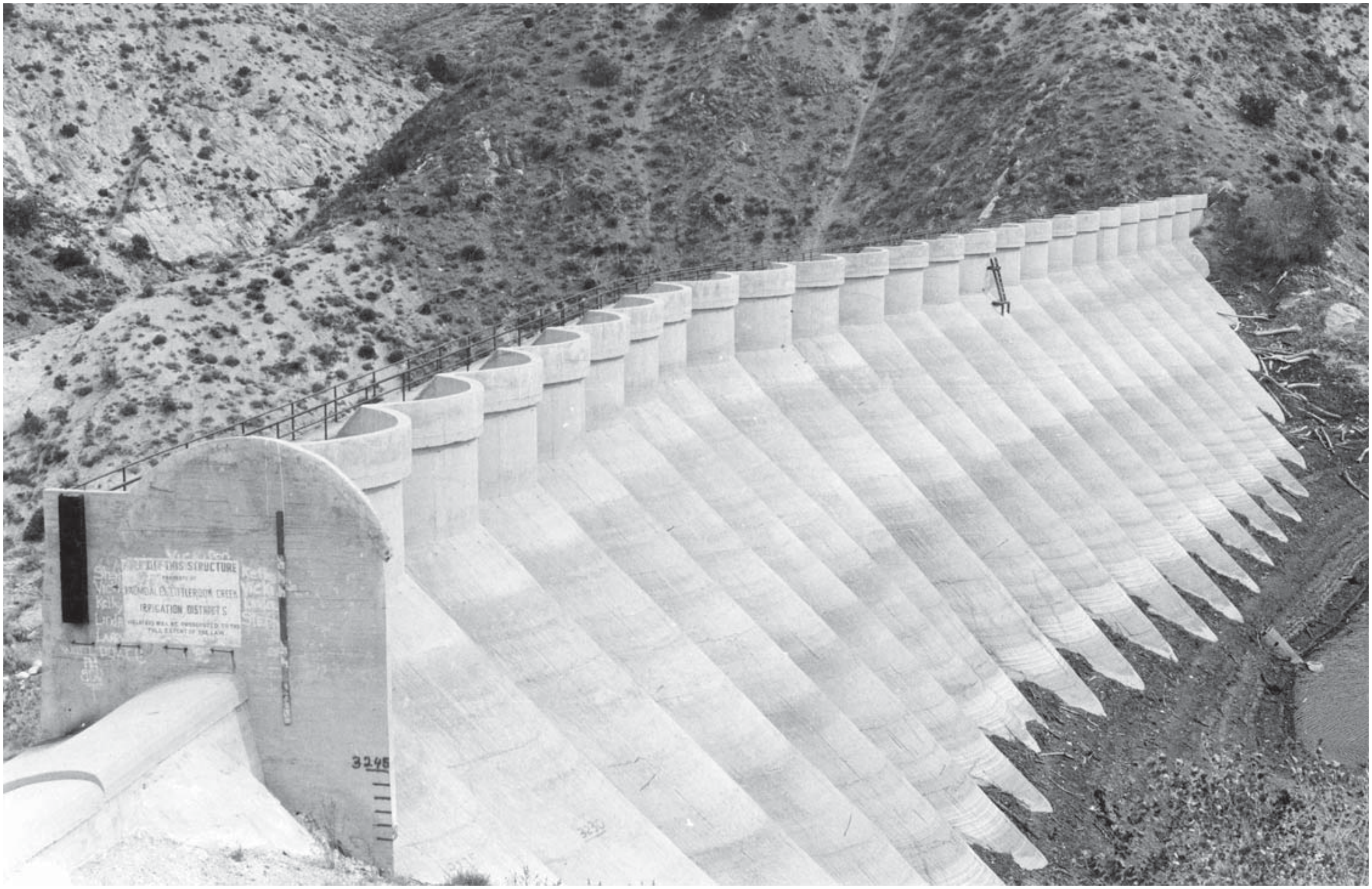


no multiple arch dam design more than 150 feet tall or featuring arches less than 15 inches thick. This seemingly capricious action was justified on grounds that multiple arch technology was too new and uncertain to warrant the risk of using it for high dams. 150 feet and 15 inches were chosen as limiting dimensions and, despite Eastwood's protestations that the restriction had no valid technological basis, McClure held fast to his decree. From 1918 through 1922 the irrigation districts petitioned and implored McClure, his staff and at least three outside engineering consultants to change course and approve Eastwood's design.

Seeking a way around McClure's objections, in December 1918 the irrigation districts also initiated a plan to contract out the dam project to the Palmdale Water Company so that the State Engineer could be bypassed and the design authorized by the (presumably supportive) Railroad Commission. As part of this initiative Eastwood developed a "radial plan" design that represented a significant innovation extending beyond his earlier projects. Despite high hopes that use of the "water company" would sidestep McClure, the irrigation districts and Eastwood were stymied when the Commissioners of the Railroad Commission (not the agency's Hydraulic Division) voted to authorize the project only if the State Engineer approved "further details." Consulting engineer Walter Huber, who later served as President of the ASCE,

Figure 13

Upstream side of Littlerock Dam in 1979. The dam as-built required 25,000 cubic yards of concrete and featured 24 foot span arches with minimum arch thickness of 12 inches. Note the angle in the dam, which provides evidence of the practicality of Eastwood's "radial plan" proposal. The review process dragged out for four years, but finally the State Engineer approved the design. [Author's Collection]

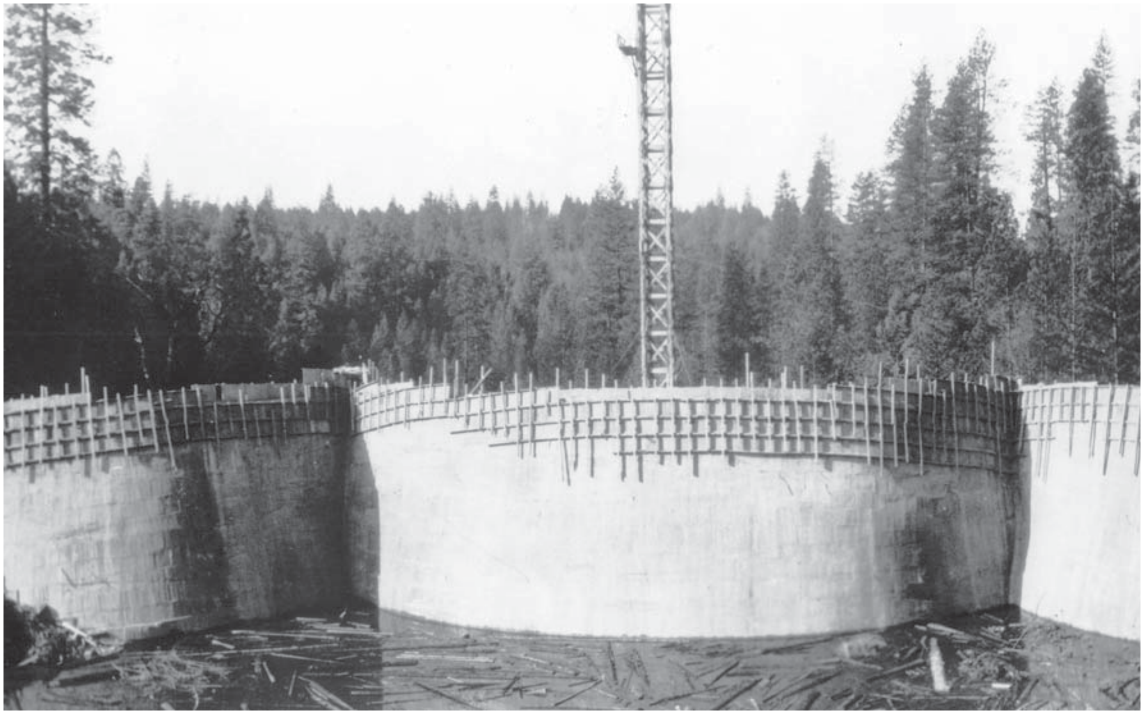


counseled State Engineer McClure that Eastwood's proposed design would at the very least require "radical modification" and urged him to withhold approval of "details" as requested by the Railroad Commission. Later, Huber would decry the radial plan proposal as "a freak design." McClure followed Huber's advice and, with the leadership of the Railroad Commission unwilling to proceed without the State Engineer's support, the Eastwood's "radial plan" proposal died on the drawing boards in the summer of 1919. From that time forward the two irrigation districts would interact directly with the State Engineer's office in seeking approval for a new storage dam. Consideration reverted to a straight-crested multiple arch design proposal, but one in which Eastwood included an angle to better accommodate the design to the site topography.[30]

For many months the regulatory review process instituted by

Figure 14

Webber Creek Dam near Placerville, 1924. Built by the El Dorado Water Company and approved by the California Railroad Commission, this 90 foot high, 300 foot wide structure was Eastwood's only "triple arch" design built before he died. The dam features a maximum arch thickness of 12 feet and, if completed to original planned height of 115 feet, would have required about 5,500 cubic yards of concrete. Construction costs were reduced because the three-arch design obviated the need for elaborate and expensive formwork. [Water Resources Center Archives]



California's 1917 dam safety law led nowhere for the Littlerock proposal, or at least nowhere that Eastwood wanted to go. Much time and energy was spent by the state engineer's office pondering what level of shearing stresses in the buttresses should be deemed acceptable and, in turn, what would be the proper way to mathematically calculate such stresses. In early 1921 McClure began to reconsider his position on approving the Littlerock Dam but he refused to budge on the minimum arch thickness. Another year passed, and finally he relented on the arch dimension in the spring of 1922. McClure's ultimate approval of the design was not predicated on a new appreciation of the design's virtues, but instead rested in part upon a reinterpretation of how the structural height was measured. Rather than consider the height to comprise the distance from deepest foundation to the crest (which was—and still is—the widely accepted measure of dam height) McClure apparently chose to calculate the height as running from the top of the streambed to the crest and by this measurement it was to be only 158 feet high. The design as approved in May 1922 certainly exceeded McClure's previously imposed 150 foot limit but, through a bit of definitional subterfuge, a way was found to justify its construction without admitting a dramatic change in policy by the State Engineer.

The exact reason for McClure's change of heart remains uncertain at distance of almost 90 years, but it appears to have been a political accommodation made to the two irrigation districts. That is certainly how Eastwood perceived the situation, as he had counseled the irrigations district in 1918 that McClure's initial decision to block any multiple design more than 150 feet high "was apparently all a trumped [up] and inspired thing to knock out your districts… [for] if you do not build a multiple arched dam, you cannot build any kind of dam, for no type can be built within the economic limits of your bonding limit."[31] The political character of the design approval process for the Littlerock Dam is reflected both in the lengthy review undertaken by the State Engineers' office and in the seemingly arbitrary way that approval was eventually justified.

Figure 15

In the 1920s Eastwood innovated with "curved face" multiple arch designs in an effort to reduce concrete quantities. He never built such a design in California, but the Cave Creek Dam north of Phoenix is probably his most remarkable and elegant dam. Completed in 1923, the 1,700 foot long dam features 44 foot span arches (maximum thickness 12 inches) and a maximum height of 120 feet. In total it required only 19,000 cubic yards of concrete—a little more than 10 cubic yards per lineal foot. [National Archives]

Passage of the 1917 dam safety law did not necessarily mean that Eastwood's ability to innovate with ever larger multiple arch dams would be slowed if not stifled in California. But that is exactly what happened. As it turned out, the Littlerock Dam was completed in June 1924 and Eastwood died two months later at age 67. Further battles with the State Engineer were obviated by his death and innovations such as the "curved face" design that he was able to use for the Cave Creek Dam in Arizona and the Anyox Dam in British Columbia (both completed in 1923) never bore fruit in California. And the only example of an Eastwood "triple arch" design was built for the Eldorado Water Company near Placerville, Calif. In 1923-24 and supervised by the Railroad Commission.

The legacy of the Littlerock dispute lingered within the State Engineer's office and a predilection towards massive dams became rooted in the agency and in consultants such as Walter Huber. John R. Freeman apparently never interacted directly with the State Engineer in advocating massive dams, but Freeman did again clash with Eastwood over dam proposals in San Diego County in the early 1920s. In a 1924 report to the San Diego Council he strongly urged the construction of "massive concrete gravity" dams that adhered to "the standard adopted by… the cities of Boston and New York for their high dams."[32] Since the first time he had clashed with Eastwood over Big Meadows in 1912-13, Freeman had served as President of the ASCE (1922) and his overt advocacy of massive dam technology carried great weight within the profession.

In California, the massive tradition advocated by Freeman found fertile ground in San Francisco and Los Angeles and in the 1920s both of these cities built major concrete gravity dams. One of these, San Francisco's Hetch Hetchy (or O'Shaughnessy) Dam, remains in service today. The other, Los Angeles's St. Francis Dam, experienced a very different fate following its completion in May 1926. A few minutes before midnight on March 12, 1928 the St. Francis Dam collapsed and sent 12 billion gallons of water surging through the Santa Clara Valley. By the time the flood washed

Figure 16

St. Francis Dam north of Los Angeles soon after completion in 1926. This 200 foot high concrete gravity dam was built by the City of Los Angeles under the "municipal exemption" codified in the state's 1917 dam safety law. Chief Engineer William Mulholland supervised the design and construction of the dam without review by state authorities or outside consulting engineers. [Author's Collection]

into the Pacific Ocean shortly before daybreak over 400 people lay dead amidst a 50-mile long trail of carnage and destruction. People immediately began to ask: why did the dam fail? And upon learning that—thanks to the "municipal exemption" provided by the 1917 dam safety law—it had been built without any outside review of the plans developed by Chief Engineer William Mulholland and his staff, a clamor arose for a new and comprehensive dam safety law.

The St. Francis Dam Disaster and Boulder Dam

The full story of the St. Francis Dam disaster is beyond the scope of this essay.[33] But suffice it to say that the concrete curved gravity dam built by the City of Los Angeles under the direction of William Mulholland was a deficient design that—because of ill-advised design changes made after the start of construction, the absence of a foundation cutoff wall, the lack of foundation grouting, and minimal subsurface drainage—fell well short of what other gravity dam engineers of the 1920s considered to be acceptable practice. The deficiency of the design was exacerbated by foundation conditions that were susceptible to subsurface seepage and allowed for significant uplift pressures to be brought against the base of the dam. In the abstract, the foundations at the site could likely have supported a more amply dimensioned (and more expensive) concrete gravity design; but the porous character of the fracture schist that formed the east abutment at St. Francis was ill-suited for a gravity structure lacking features that could have impeded sub-surface flow and lessened the destabilizing effect caused by uplift pressure. The conjoining of less-than-ideal foundations and a design that did little to ameliorate the effect of uplift proved to be a deadly combination.

Very quickly after the collapse, the failure of the St. Francis Dam was linked to the lack of any outside review of the Mulholland's plans. Because the design was built under the umbrella of the municipal exemption in the 1917 dam safety law, Mulholland's failings were widely interpreted as compelling evidence that all dam engineers should be supervised and regulated under state authority. In this context, it is important to point out that there was nothing inherent in the municipal exemption that required Mulholland to adopt a deficient design. For example, M. M. O'Shaughnessy of San Francisco had operated freely in building the Hetch Hetchy Dam and his concrete curved gravity design

Figure 17

Remains of the St. Francis Dam after its catastrophic collapse on March 12, 1928. The surviving center section of the structure was soon heralded by some engineers—including an investigating committee convened by Governor C. C. Young—as evidence of the great strength of gravity dam technology. [Author's Collection]

suffered none of the deficiencies present in the St. Francis Dam. O'Shaughnessy proved fully capable of building a safe (if rather expensive) concrete gravity dam without the benefit of supervision by the State Engineer and this is a point worth reinforcing. And presumably the efficacy of Eastwood's Littlerock Dam benefited little, if at all, from the lengthy review process instituted by the State Engineer. Put another way, it is reasonable to believe that Eastwood, as he had at Hume Lake and Big Bear Valley a decade earlier, would have acted just as responsibly in designing the multiple arch Littlerock Dam as O'Shaughnessy did in designing the massive Hetch Hetchy Dam.

The absence of state supervision does not inevitably lead to deficient design, but in the aftermath of the St. Francis disaster much criticism was directed toward the municipal exemption. Not surprisingly, demands arose for enactment of new legislation that would bring all non-federal dams in California under state regulation. But what is surprising is that the suitability of massive concrete gravity dams—the basic technology used at St. Francis—experienced almost no criticism at the hands of the newly empowered State Engineer's office. And multiple arch dam technology, which had nothing to do with the failure at St. Francis, soon attracted such intense regulatory scrutiny that it essentially disappeared as an acceptable alternative for new water projects. Why would this be?

The history of California dam building in the wake of the St. Francis disaster is only understandable if assessed in a context that appreciates the political nature of the proposed Boulder Canyon Project and what became the Hoover Dam.[34] The site of Boulder/Hoover Dam may have spanned the Colorado River between Nevada and Arizona, but the Boulder Canyon Project Act was spawned and driven by a southern California juggernaut.

Figure 18

William Mulholland a short distance upstream from the proposed site of Hoover/Boulder Dam, circa 1925. Mulholland did not participate in the design of the huge dam that was to impound the Colorado River, but he was closely associated with the Boulder Canyon Project Act and the related Metropolitan Water District of Southern California. [Author's Collection]

Starting in the early 1920s, both the Imperial Irrigation District in the Imperial Valley and urban boosters in Greater Los Angeles marshaled an enormous political effort to win passage of the act (widely known as the Swing-Johnson Bill because of its sponsorship by Representative Phil Swing and Senator Hiram Johnson, both of California). Although William Mulholland played no role in designing the proposed Boulder Dam, he did play an active role in lobbying for the Swing-Johnson Bill and testified before Congress in its support. As it turned out, the seven year long effort to win congressional approval for the Boulder Canyon Project poised on the brink of success in March 1928. For supporters of the project the St. Francis collapse could not have come at a worse time because it drew attention both to the dangers posed by large-scale dams and to Mulholland's central role in the disaster. Opponents of the proposed Boulder Dam—including both political leaders in Arizona and lobbyists for America's investor-owned electric power industry—were more than willing to use the disaster to their own advantage.

Both the St. Francis and the proposed Boulder design comprised massive concrete curved gravity structures and California's political leadership quickly sought to separate the two dams in the eyes of the public. The politician most focused on this issue was Governor C. C. Young, a progressive Republican who had championed authorization of Boulder Dam in his 1926 election campaign.[35] Less than a week after the St. Francis failure he convened a select group of engineers to investigate the disaster and report upon the cause of the collapse. Heading this commission was A. J. Wiley, a respected engineer and gravity dam designer who had previously worked with the Bureau of Reclamation in developing the Boulder Dam design. On Sunday March 18 Wiley meet with Governor Young in Sacramento prior to the start of the commission's work in Los Angeles the next day. A week later on March 25 the commission completed its report. The next day Wiley met with the Governor to convey its findings and on Tuesday March 27th the report was made public. A mere two weeks had passed since the dam's tragic collapse.

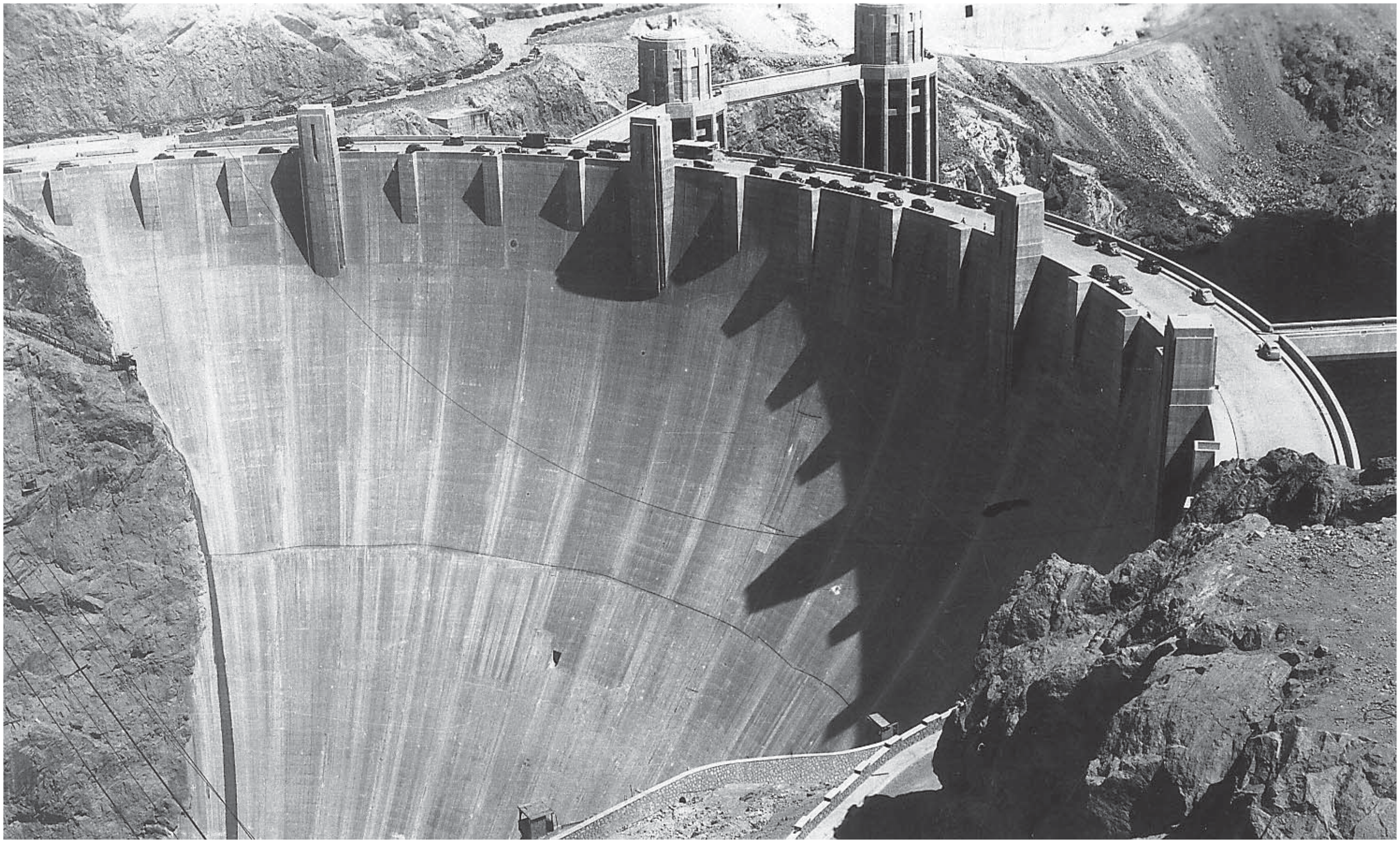
In its report the commission acknowledged deficiencies in Mulholland's design (including the lack of cutoff walls, the absence of foundation grouting, and the paucity of drainage wells); they also acknowledged that they could not ascertain precisely "the manner and chronological order" of the collapse. Nonetheless the commission was adamant that "the failure of St. Francis Dam was due to defective foundations." With equal adamancy the commission offered reassurance that there was "no reason to believe that the accepted theory of gravity dam design is in error…" Perhaps most remarkably, the commission further proclaimed that:

> "the middle section [of the St. Francis Dam] which remains standing even under such adverse conditions [offers] most convincing evidence of the stability of such structures when built upon firm and durable bedrock."[36]

With this latter assertion, the commission's investigation into the cause of the St. Francis failure became a forum championing the merits of concrete gravity dams. In this, the surviving center section was trumpeted as symbolizing the massive technology's great strength.

Figure 19

Hoover/Boulder Dam circa 1940, probably the most famous concrete gravity dam in the world. Yes, it is curved which might lead an observer to believe that it is an arch dam. But the dimensions are so bulky (with a max height of 726 feet and a max thickness of more than 600 feet) that it exemplifies the Massive Tradition par excellence. During the 1930s, massive dams proliferated across the American landscape while dams in the Structural Tradition were only rarely built. [Author's Collection]



The political purpose of the report, and the way that it focused attention on foundation conditions and not on the dam design itself, is evident in two telegrams soon sent to Representative Swing. Immediately upon completion of the commission's report—and even before the Governor had seen it—State Engineer Edward Hyatt (who assumed the office following McClure's death in 1926) wired Swing in Washington, D.C. with a special reassurance:

"Report of the Investigating Committee St. Francis Dam just completed but not yet in hands of Governor Young Stop Statement to you to the effect that there is absolutely no relation between the failure of the St. Francis Dam and the safety of the proposed Boulder Canyon Dam can be sent best advantage tomorrow morning after conference between Governor Young and A J Wiley Chairman of the investigating commission..."[37]

The next day (March 27) Governor Young did indeed meet with Wiley, and immediately thereafter he sent his own telegram to Congressman Swing. In this he avowed that what occurred at St. Francis bore no relation to anything that could be ascribed to the Hoover/Boulder site:

> "I have positive assurance from A. J. Wiley, Chairman of Commission… that the bedrock there [for Boulder Dam] is so sound, hard and durable and so different from the very soft foundation of the St. Francis Dam, that the failure of St. Francis Dam need cause no apprehension whatever regarding the safety of the proposed Boulder Canyon Dam."[38]

In addition, Governor Young further emphasized to Swing that the failure was most assuredly not related to gravity dam technology:

> "The report of the investigating committee also states that there is nothing in the accepted theory of gravity dam design that is in error or that there is any question about the safety of concrete dams designed in accordance with that theory when built upon ordinarily sound bed rock but that on the contrary the action of the middle section of the St. Francis Dam that remained standing even under such adverse conditions is most convincing evidence of the stability of such structures when built upon such firm and durable bedrock as is present in Boulder Canyon."[39]

The worst dam disaster in 20th century American history involved the failure of a poorly designed concrete gravity design and the most prominent engineering investigation of the disaster paid special attention to reassuring the public that the technology itself was not to blame for the tragedy. The reason for this related directly to a politically motivated desire to protect the proposed Boulder Dam from attack by opponents of the Boulder Canyon Project Act. But the defense of massive gravity dam design that resulted from the St. Francis tragedy had a broader consequence, one in which the technology was heralded—and widely embraced by a willing public —as constituting the premier standard for large-scale dam design.

The words "psychology" or "psychological" were never used when engineers such as Wiley called attention to the surviving center section of the St. Francis Dam and heralded it as comprising "most convincing evidence of the stability of such structures." Nonetheless, such a defense can be easily aligned with the way, fifteen years earlier, John Freeman had criticized the visual appearance of "lace curtain" multiple arch dams as falling short of the standard set by massive gravity dam technology. Freeman played no official role in the investigation of the St. Francis disaster but, because he was so closely associated with gravity dam technology, engineers in California provided him with reports on the collapsed dam. Walter Huber wrote to him less than two weeks after the tragedy, counseling that "briefly the whole story is clearly one of lack of suitable foundations." More significantly, and even before the Governor's commission had issued its report, Huber assured Freeman that "the center section of the dam… is the one great witness of the stability of a gravity section founded on a solid foundation." Preaching to the choir perhaps in his praising of the Massive Tradition to Freeman, Huber nonetheless saw in the St. Francis disaster a need to assure all who would listen that gravity dam technology indeed represented a worthy standard.

Dam Safety after St. Francis

In the aftermath of the St. Francis disaster, a public clamor arose calling for a new dam safety law that would eliminate the municipal exemption and place all authority in one state office. For example, the report by the governor's commission urged that in the future all dams be "erected and maintained under the supervision and control of state authorities… with the police powers of the state… extended to cover all structures impounding any considerable quantities of water."[40] Given the horrible destruction wrought by a dam built without state supervision, it was difficult for anyone to overtly oppose such a proposal. One of the few who did was M. M. O'Shaughnessy, the San Francisco engineer who in 1917 had lobbied for protection from unwanted interference by State Engineer Wilbur McClure. O'Shaughnessy complained that the St. Francis catastrophe had created "an hysteria" whereby citizens and legislators "have practically lost their heads on the subject of dam design and construction…" but this time around his objections carried far less weight than they had a decade earlier.[41] Comprehensive dam safety legislation was coming, whether engineers like O'Shaughnessy wanted it or not.

Although largely kept out of public discussion there were fears that, if carried too far, increased state regulation of dams could impede economic growth. After all, what if vital development of California's water resources were to be blocked by adherence to an unrealistic standard of safety? In early April 1928 State Engineer Hyatt acknowledged problems that might result from excessive zeal in regulating dam construction:

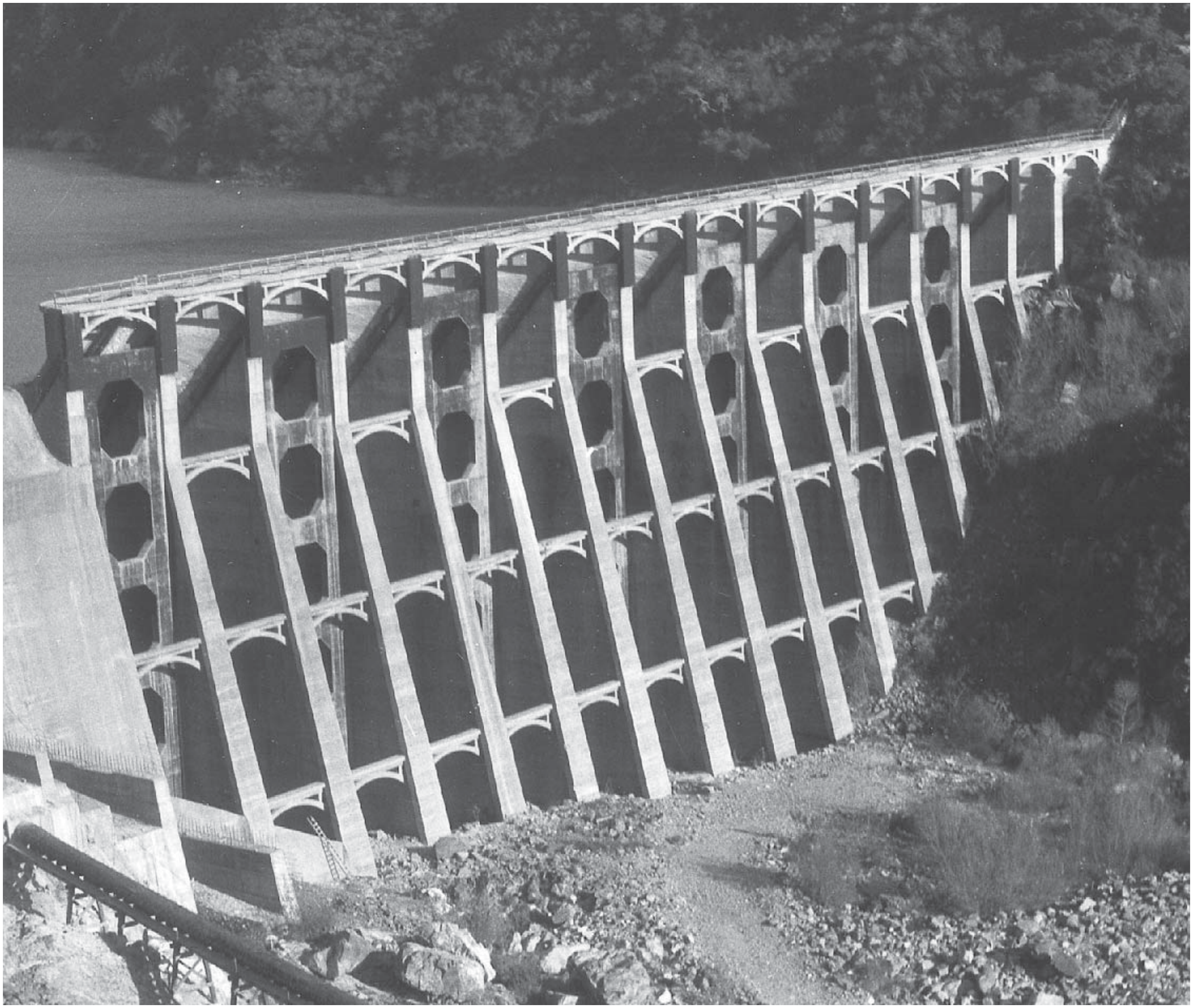
> "[T]he failure of the St. Francis Dam has greatly disturbed public confidence in the safety of all dams, and for a time at least, proposals for the construction of new structures are going to face unmerited opposition no matter how carefully supervised by public authority. Even among competent engineers there will be a tendency toward undue conservatism… we feel that we must exercise great care to avoid insisting upon safeguards beyond the actual needs since many meritorious projects might be thereby rendered financially infeasible."[42]

Hyatt's concern was real, but it appeared to have little effect on the new dam safety law enacted in the summer of 1929. From that time on the municipal exemption was a thing of the past. So too, the Railroad Commission lost its authority over dam construction by public corporations. All supervisory power was now concentrated in the hands of the State Engineer's office and any entity other than the Federal Government who desired to build or operate a dam over ten feet high in the state of California now required the State Engineer's approval.

Previously the Railroad Commission had provided a regulatory environment amenable to innovations Eastwood had brought to the practice of dam design. The State Engineer's office had been much less supportive of Eastwood's work and, with passage of the new dam safety law, the antipathy evident in the bureaucratic battle over the Littlerock Dam became more formalized. This occurred through a special panel of engineers dubbed the "Multiple Arch Dam Advisory Committee" and charged by State Engineer Hyatt to evaluate the status and viability of multiple arch technology. Headed by Walter Huber (the same engineer who had assured John Freeman of the symbolic strength of the St Francis Dam's surviving center section, and who also had denigrated Eastwood's radial plan design for Littlerock a decade earlier), this committee issued a report in 1932 that had little good to say about multiple arch dams. Belittling the technology as a "cheap substitute," the committee begrudgingly admitted that "some of them [multiple arch dams] have been designed under competitive conditions resulting in structures successfully answering certain mathematical requirements…" But meeting "mathematical requirements" was not sufficient, because the committee considered the technology (in a manner reminiscent of Freeman's "psychological" objection to Big Meadows) to be "hardly adequate from other points of view."[43] Soon, the State Engineer's office focused its sights on Eastwood's Lake Hodges Dam in San Diego County. Completed in 1918, the buttresses at Hodges developed some temperature/expansion cracks that, although unaffected by hydrostatic forces acting on the structure, were perceived as evidence of weakness. The solution? Require the construction of a new bracing system that would, perhaps not coincidentally, make the downstream façade appear more massive. The attribute of slenderness that is endemic in structural art came to hold no allure in California in the post-St. Francis era of dam building. [44]

Figure 20

After the St. Francis disaster, California revised its dam safety law to eliminate the "municipal exemption" and place all non-federal dams under the authority of the State Engineer. A special advisory committee on multiple arch dams was soon formed and in 1932 this committee issued a report criticizing the technology. The State Engineer's office then began working to "strengthen" existing multiple arch dams. Eastwood's Lake Hodges Dam in San Diego was the first to be altered by adding additional bracing between the buttresses. This supposed strengthening also worked to reduce the "lace curtain" effect and make the downstream side appear more massive. [Water Resources Center Archives]



Even before Huber's advisory committee issued its report, engineers in California sensed that the new dam safety law, in a manner akin to the fears earlier expressed by Hyatt about "undue conservatism," would equate dam safety with increased construction cost. In a 1931 paper published as part of an ASCE dam safety symposium, A. W. Markwart, Vice President of Engineering for the Pacific Gas and Electric Company pointedly observed: "it is not improbable that the tendency will be to require dams to be constructed stronger than actually necessary. Such excess strength can only be had from capital expenditures greater than have been required in the past…"[45] In other comments published as part of the ASCE symposium, the European-trained engineer Fred Noetzli—a prominent advocate of thin arch and multiple arch dams who in a 1924 ASCE Transactions article had opined that "the gravity dam is an economic crime"—also expressed concern that that California's new law would foster adaptation of massive gravity dam technology at the expense of other alternatives. In Noetzli's eloquent phrasing: "there is no good reason why the most expensive type, namely the gravity dam, should receive first and sometimes sole consideration."[46] Noetzli died unexpectedly in 1933 and, with his passing, the Structural Tradition of dam design that had once found such forceful expression in California entered a long period of decline.[47] Although some thin arch dams were subsequently constructed in the state, since the passage of the 1929 law the author knows of no new multiple arch dams that have been approved and built in California.[48]

Conclusion

The easy lesson taught by the St. Francis Dam disaster was that freedom was bad and regulatory supervision was good. Thus the St. Francis catastrophe spurred a drastic strengthening of the state's dam safety apparatus. In addition, the disaster also made it politically imperative that the massive gravity technology proposed for the Boulder Canyon Project not be smeared simply because it could be tied to St. Francis. As a result, the Massive Tradition came to assume a professional stature within California's dam safety bureaucracy that John Freeman would have considered most reasonable and appropriate. In contrast, innovators in the Structural Tradition were accorded little favor by the new regime and Noetzli's fears that, going forward, gravity dams would "receive first and sometimes sole consideration," indeed proved prescient.

Since 1929 California has cultivated a reputation for sustaining one of the most demanding dam safety bureaucracies in the world. But it may also be that efforts to insure dam safety have worked to suppress innovation in the development of new designs. Certainly Eastwood would have found that to be true, as one of the first major regulatory actions taken following passage of the 1929 law was to investigate, and then demonize, multiple arch technology. The vibrant innovation that defined Eastwood's work in the 1910s and 1920s shone bright when free from the chains of regulatory review or when supported by a state authority such as the Hydraulic Division of the Railroad Commission. Thus for a time in the early 20th century the structural art of dams found fertile ground in California, but the era proved short-lived. When the State Engineer's office took full control over state supervision of dams, the Massive Tradition came to the fore.

Was the decline of the Structural Tradition in California inevitable? No. Nonetheless, it is difficult not to see the strengthening of state law in 1929 as spawning a regulatory environment offering minimal encouragement to dam engineers who, following in Eastwood's path, might wish to innovate in the realm of multiple arch design. Through the course of the 20th Century, American engineering and political culture only rarely encouraged the creation of structural art and Billington has bemoaned this state of affairs in The Tower and the Bridge by noting "the relative lack of structural artists in the United States."[49] The story (and fate) of multiple arch dams in California offers an important case study illustrating why, in America, the ideals of structural art ultimately failed to flourish in the field of hydraulic engineering.

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4. Donald C. Jackson, *Building the Ultimate Dam: John S. Eastwood and the Control of Water in the West* (Lawrence: University Press of Kansas, 1995; Paper ed. University of Oklahoma Press, 2005).
5. Eastwood's stature as a structural artist is examined in Donald C. Jackson, "Structural Art: John S. Eastwood and the Multiple Arch Dam" in Engineering History and Heritage Journal, Proceedings of the Institution of Civil Engineers, Spring 2009, pp. 137-146
6. For details on the Salt Lake City's design competition for the 150 foot high Mountain Dell Dam in 1915 see Jackson, Building the Ultimate Dam; pp. 146-149. The low bid for Eastwood's multiple arch design was $138,839 while the low bid for the concrete curved gravity design came in at $226,212.
7. For a review of early dam building in California and the American West see Jackson, Building the Ultimate Dam; Chapter Two.
8. The Bowman and San Mateo (Crystal Springs) Dams are described in James D. Schyuler, *Reservoirs for Irrigation, Water power and Domestic Water Supply*, 2nd ed. (New York: John Wiley, 1909) pp. 267-74,500-02.
9. F. E. Brown, "The Bear Valley Dam," Engineering News 19 (June 23, 1888): 313-14; Sweetwater Dam is described in Schyuler, Reservoirs for Irrigation, Water power and Domestic Water Supply, pp. 213-37.
10. Elizabeth M. Sharpe, *In The Shadow of the Dam: The Aftermath of the Mill River Flood of 1874* (New York: Free Press, 2004).
11. David G. McCullough, *The Johnstown Flood*, (New York: Simon & Schuster, 1968)
12. For more on the early engineering career of John Eastwood see *Building the Ultimate Dam*. Chap. 3, pp. 41-58
13. Eastwood's work on the Big Creek project is described in Building the Ultimate Dam, Chap. 4, pp. 59-84.
14. John S. Eastwood, "Hume Lake Dam," Journal of Electricity, Power and Gas 23 (Oct, 30, 1909): 398-404; and Building the Ultimate Dam, pp. 85-98.
15. John S. Eastwood, "New Big Bear Valley Dam,: Western Engineering 3 (December 1913): 458-70; and Building the Ultimate Dam, pp. 98-108.
16. "John Ripley Freeman, Transactions of the American Society of Civil Engineers 98 (1933): 1471-76. Freeman was born in 1855 and died in Oct 1932.
17. Freeman's advocacy of massive gravity dam technology is documented in Building the Ultimate Dam. Chap. 6, pp.109-133; for example in an October 11, 1911 letter to PWPC board member Guy Earl, Freeman declared "it does not pay to carry economy to excess in dam building and there is nothing quite so satisfying as a big solid mass of concrete." (p. 116).
18. For detailed discussion of Eastwood's Big Meadows project and the opposition of John R. Freeman see *Building the Ultimate Dam*, pp. 109-34; Freeman's quotes on "psychological" and "lace curtain" are included in John R. Freeman to Arthur P. Davis, Sept 26, 1912 and John R. Freeman to H.P. Wilson, Sept 30, 1912; both letters in John R. Freeman Papers, Box 63, Institute Archives and Special Collections, MIT, Cambridge Ma.
19. John R. Freeman and Alfred Noble to H.P. Wilson, October 17, 1912, Freeman Papers. Box 63.
20. R. A. Thompson to Railroad Commission, February 7, 1913, Public Utilities Commission Records, Application No. 357, California State Archives, Sacramento, California..
21. See *Building the Ultimate Dam*, pp. 119-21,128; also see Railroad Commission of California to John S. Eastwood, March 25, 1913, Public Utilities Commission Records, Application No. 357.
22. Philip E. Harroun apparently served as the first Hydraulic Engineer of the Railroad Commission and he held the position at the time Freeman began complaining about Eastwood's design in August/September 1912. By February 1913 R.A. Thomson was serving as the commission's Hydraulic Engineer. By the latter part of 1913 R. W. Hawley had taken over the position where he remained until 1919.
23. *Building the Ultimate Dam*, pp. 140-43; John S. Eastwood, "Los Verjels Dam, A Multiple Arched Structure," Western Engineering 5 (July 1914): 7-9. Also see Public Utilities Commission Records, Hydraulic Division File #630, Sacramento.
24. *Building the Ultimate Dam*, pp. 158-160.
25. John S. Eastwood to A.W. Burchard, Oct 29, 1912, and John S. Eastwood to Railroad Commission, March 17, 1913; both letters in Big Meadows Folder #18, Eastwood Papers, Water Resources Center Archives, University of California..
26. As enacted in May 1917, the state's dam safety law appears in California Statutes, chap. 337, sec 2, (1917): 517-518.
27. Michael M. O'Shaughnessy to Edward Hyatt, State Engineer, October 3, 1928, "Supervision of Dams, 1928" folder, Public Utility Commission Records, California State Archives, Sacramento, California.
28. *Building the Ultimate Dam*, pp. 219-23. At Webber Creek Eastwood actually worked with R.W Hawley, who had left the Railroad Commission in the early 1920s, and was now serving as a consultant for the El Dorado Water Company. Chester Loveland now served as head of the Hydraulic Division; like his predecessor he was very supportive of Eastwood's work.
29. For more on the controversy involving the Littlerock Dam see *Building the*

Ultimate Dam, p. 197-209.

30. The story of Eastwood's "radial plan" design for Littlerock is told in Building the Ultimate Dam, pp. 199-202. Also see W. L. Huber to W.F. McClure, June 21, 1919; and W. L. Huber to W.F. McClure, May 28, 1920; both letters in Littlerock Dam File, Division of Safety of Dams, California Department of Water Resources, Sacramento.
31. John S. Eastwood to Burt Cole, November 27, 1918, Eastwood Papers, Littlerock Dam Folder #44, Water Resources Center Archives.
32. John R. Freeman, "Summary of Recommendations Regarding Future Extensions of Water Supply of San Diego, Cal." May 16 and May 24, 1924, report held by Water Resources Center Archive, University of California.
33. For extended discussion of the St. Francis Dam disaster see Donald C. Jackson and Norris Hundley, "Privilege and Responsibility:William Mulholland and the St. Francis Dam Disaster," California History (Fall 2004): 8-47.
34. For more on the relationship of the St. Francis Dam disaster and the proposed Boulder/Hoover Dam see Donald C. Jackson "Politics and Dam Safety: The St. Francis Dam Disaster and the Boulder Canyon Project Act" in Richard Wiltshire et al, eds. Proceedings of the American Society of Civil Engineers, Hoover Dam 75th Anniversary History Symposium, , (Reston: ASCE, 2010): pp. 1-24.
35. See http://www.californiagovernors.ca.gov/h/documents/inaugural_26.html. At his inaugural Young commented that: "The prospects are very bright that the Congress at its present session will furnish the needed relief for the south by passing the bill for the dam at Boulder Canyon. California will certainly do all she can toward this end by making clear her attitude through representatives of this administration in Washington… I feel assured that this Legislature will also meet the acute need of the south for an adequate domestic water supply by authorizing the formation of a metropolitan water district such as may permanently solve her difficulties along this line."
36. Report of the Commission Appointed by Governor C.C. Young, p. 18.
37. Telegram from Edward Hyatt to Phil D. Swing, March 26, 1928; St. Francis Dam Disaster file, Division of Safety of Dams, Sacramento, California.
38. Telegram from C. C. Young to Phil D. Swing, March 27, 1928; St. Francis Dam Disaster file, Division of Safety of Dams, Sacramento, California.
39. Ibid.
40. Report of the Commission Appointed by Governor C.C. Young, 18. Also see "Dam Oversight Urged on State: Governor Asked to Move for Supervision Laws." Los Angeles Times, April 26, 1928.
41. M. M. O'Shaughnessy, comments on "Public Supervision of Dams: A Symposium," Transactions of the American Society of Civil Engineers 98 (1933): 853.
42. Edward Hyatt to M.R. McKall, April 7, 1928, "St. Francis Dam" file, Division of Safety of Dams., Sacramento, California.
43. H.W. Dennis, G..A. Elliot, and Walter L. Huber to State Engineer Edward Hyatt, September 15, 1932, Folder #630, Walter L, Huber Papers, Water Resources Center Archives, University of California.
44. Fred D. Pyle, "Hodges Dam Strengthened," Engineering News-Record 117 (Nov. 5 1936): 644-47.
45. A. W. Markwart, "Recommendation for Legislation and Application of Law" in "Public Supervision of Dams: A Symposium," Transactions of the American Society of Civil Engineers 98 (1933): 828-835. Quote on p. 830.
46. Fred Noetzli, "An Improved Type of Multiple Arch Dam" Transactions of the American Society of Civil Engineers 87 (1924): 410; Comments by Fred Noetzli in "Public Supervision of Dams: A Symposium," p. 865.
47. For more on Noetzli and his work on multiple arch and thin arch dam designs see Jackson, *Building the Ultimate Dam*, pp. 172-174. This reference also includes material on Lars Jorgenson and B.F. Jakobsen who also promoted multiple arch and thin arch designs in California in the 1920s. Also see David P. Billington and Donald C. Jackson, *Big Dams of the New Deal Era: A Confluence of Engineering and Politics* (Norman, OK: University of Oklahoma Press, 2006), pp. 57-65, for more on Noetzli's career as a dam designer and theorist.
48. The Sutherland Dam in northern San Diego County was completed in the early 1950s, but it was a multiple arch design started in the mid-1920s and long left dormant after the St. Francis disaster transformed dam safety regulation in California. Several score of major massive concrete gravity and massive embankment dams have been built in California since enactment of the 1929 dam safety law.
49. Billington, *The Tower and the Bridge*, p. 53.

DEVELOPMENT OF AN ENGINEERING ORGANIZATION / DEVELOPMENT OF AN ENGINEER

Reflections on the Value of an Undergraduate Research Experience

Abbie B. Liel

In the spring of 2000, near the end of my sophomore year at Princeton University, Professor David Billington asked me if I would be interested in helping with one of his research projects. With a little trepidation and much enthusiasm, I agreed, and spent the summer and the next two academic years researching the early engineering organization at the Tennessee Valley Authority. I have been continuously engaged in structural engineering-related research since that first summer. Over time, I have realized that in the process of investigating and telling the story of the engineering organization at TVA, I learned at least as much about research methods, my own career aspirations, and the importance of Professor Billington's mentorship, as I did about the TVA.

Development of the Engineering Organization at the Tennessee Valley Authority

The goal of this study was to examine the development of the engineering organization at the Tennessee Valley Authority (TVA) during its early years, and to understand how key decisions, such as the decision to do dam construction "in house", were made. Although much had been written about the TVA, particularly the politics of its early proponents in the 1920s, its origins during the Great Depression, the controversy of creating a multi-state organization to manage a river basin, the conflict between its early board members, and the technical features of its concrete dams, little had been written about the development of the engineering organization within this unique and complex political instrument.[1] The story of TVA engineering management during these early years provides an important case study of how an organization grew from its inception in 1933, to build major engineering works, including the planning, design and construction of six major dams, by 1940 (Table 1).

As part of his "First Hundred Days" as President, Franklin Roosevelt signed the act authorizing the Tennessee Valley Authority (TVA) on May 18, 1933, and chose Arthur Morgan as the organization's first chairman. Morgan was well known for developing the Miami River flood control plan for the Miami Conservancy District, which covered much of central Ohio, between 1915 and 1921, and for serving as president of Antioch College from 1921-1933. Figure 1 shows a photo of Morgan with the two other members of TVA's first Board of Directors: Harcourt Morgan, then president of the University of Tennessee and a specialist in agricultural science, and David Lilienthal, a young lawyer for the Wisconsin Public Services Commission specializing in electric power regulation. In the summer of 1933, these three men were charged with the daunting task of launching the new Authority, an agency with no employees, no organizational structure, and no

Figure 1

The first TVA Board of Directors: Harcourt Morgan, Arthur Morgan and David Lilienthal. [Reference: TVA Archives] technical expertise in the building of concrete dams (the Miami Conservancy District had relied solely upon earthen embankment dams for flood control). Nonetheless, the demands of Roosevelt's New Deal program to resuscitate the American economy pervaded the young organization and the Board of Directors desired to quickly begin construction in order to reconfigure the physical, social and economic structure of the Tennessee Valley.

Dam	Year completed
Norris	1936
Wheeler	1936
Pickwick Landing	1938
Guntersville	1939
Chickamauga	1940
Hiwassee	1940

Decisions had to be made as to how construction would be carried out, and how the TVA would be organized. Under Morgan's leadership, TVA began by removing the U.S. Army Corps of Engineers from the Tennessee Valley. Although the Corps of Engineers had already made plans for development of the river basin, both Roosevelt and Morgan felt that the duality of the New Deal's engineering and social goals for the region could be better accomplished by a new and completely autonomous agency. The Corps of Engineers' legacy was a detailed report planning development in the Tennessee Valley, which proposed Norris Dam (known to the Corps as the "Cove Creek Dam") on the Clinch River, and Wheeler Dam, on the Tennessee River above the existing Wilson Dam, as the first two construction priorities.[2]

A central question related to the early TVA engineering organization, then, is how the TVA grew the engineering expertise needed to design and build their first major project, Norris Dam (Figure 2). Because of a desire to start work as quickly as possible, the Board of Directors decided to engage the Bureau of Reclamation, the federal dam-building agency with the greatest experience in large concrete dams, to design both Norris and Wheeler dams. The Bureau of Reclamation engineers, led by John L. Savage, reviewed the designs already prepared by the Corps of Engineers, redesigned the dams, and furnished TVA with complete designs and specifications. Although Sherman Woodward, a TVA water resources engineer, reportedly deemed the original Corps of Engineers' designs as "naïve and in need of improvement,"[3] the decision to discard the Corps of Engineers' designs seems to have been largely based in politics rather than engineering and, particularly, Morgan's well-documented dislike of the Corps of Engineers (who had opposed his advocacy of flood control dams instead of levees while he led the Miami Conservancy District).[4] In fact, the final straight-crested concrete gravity design of Norris Dam has the same general form as the Corps of Engineers' Cove Creek proposal, though it has a lower reservoir elevation and – most significantly – discards plans for a cumbersome navigational lock. The Bureau engineers also utilized plans for their recently completed Madden Dam, in the Panama Canal Zone, as an aid in developing the Norris design.[5]

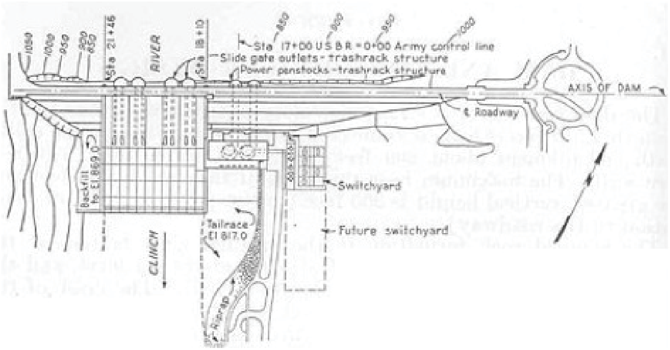
The Corps of Engineers' preparation work in studying the Tennessee River watershed, as well as the engineering expertise provided by the Bureau of Reclamation and mapping assistance from the United States Geological Survey, allowed TVA to begin construction of Norris and Wheeler Dams almost immediately. This quick start was considered to be imperative, in light of the political need to create jobs and to put people to work during the Great Depression. TVA hired construction forces at the same time as the Bureau finalized the dam design. By December 1935, the organization had grown to 14,437 workers.[6]

Force Account Construction

A critical decision made in 1933 was the choice to build the dams using the organization's own construction employees, what in the early 20th century was called the "force account" construction method, rather than putting design and specifications out for

Figure 2

Three views of Norris Dam: (a) as drawn in TVA reports and design documents [Reference: Norris Project Report], (b) as shown in historic photographs [Reference: Library of Congress], and (c) as it appeared in June, 2000 when the author and Princeton University graduate student Sinead Mac Namara visited.



contractors' bids. This decision was unique to TVA, as all major federal American dams built in the 1930s—except those in the Tennessee Valley—relied upon the traditional approach. Throughout its early years, the TVA relied upon the force account method of construction for its dams.

Arthur Morgan's experience at the Miami Conservancy District greatly influenced the decision to use the force account method at TVA. Although he had originally planned to use the traditional contracting method for the Miami Conservancy flood control structures, World War I led to fluctuations in materials and wages, and hence to large contingencies in contracts. Unwilling to accept these uncertainties, Morgan chose to hire his own workforce at the Miami Conservancy District.[7] This experience, which he compared with his earlier years in private engineering practice, led Morgan to criticize the customary contract forms and specifications for their "ambiguity, repetition, [and] stereotyped phraseology."[8] Morgan viewed the development of the Tennessee Valley as a scaling-up of the work he had done at the Miami Conservancy, and wanted to incorporate the same construction methods. In his later writings, he claimed, "the idea to take this course [the force account method] was mine."[9] Of course, force account construction had not been invented by Morgan and had previously been used by other public agencies and private companies. Perhaps most notably William Mulholland used it to build the Los Angeles Aqueduct in 1907-1913; force account methods had also been used by Mulholland to build Los Angeles' St. Francis Dam (1924-26) and had come under criticism by the Association of General Contractors when the St. Francis Dam collapsed in March 1928, killing more than 400 people.[10] In the wake of the St. Francis disaster, Morgan took no small political risk in adopting force account methods for the TVA.

The TVA directors believed that the force account method would shorten the time needed to complete the projects. At a July 29, 1933 board meeting, the directors said that plans for Norris Dam could not be finished for six months and that "it would be difficult to take bids until the plans are finished, but it is possible to begin work very soon by force account."[11] Though the Bureau of Reclamation's construction work had almost always been done through the traditional bid-contracting system, Savage, the Bureau's chief design engineer, supported the choice of the force account method. Minutes of the same board meeting read, "Mr. Savage believes the best and most economical results will come from the direct responsibility of the construction superintendent to the Authority, without the intervention of a contractor."[12] Praising the decision after the fact, Gordon Clapp (later a chairman of the TVA) described the shortened time to completion as the major advantage of the force-account method: "Building a dam by contract, in fact, is to build a dam at least twice, once on the drawing boards before you move a cubic yard of dirt and building it again on the site."[13]

In addition, the TVA board believed that the force account method would facilitate the realization of improvements that could be made and added to the as yet unfinished projects, a concept Morgan referred to as "dynamic design". In describing the advantages of TVA's approach, Morgan wrote, "I had found [at Miami Conservancy] that in large outdoor constructions there would almost certainly be actual conditions that could not be anticipated at the start."[14] These observations were supported by engineers such as Ross White, construction superintendent at Norris Dam, who argued that "it may be necessary to change substantially the foundation plans [for Norris Dam] when the excavation for the foundation has exposed the nature of the underlying rock."[15] The implementation of the force account method meant that the final Norris design was only a few weeks ahead of construction. Morgan later claimed that several changes at Norris Dam made late in the design process, including the decision to increase concrete density, thereby increasing the safe reservoir level by 10%, would have been impossible to make in the context of traditional construction contracts.[16]

The Board of Directors further justified the force account method because it would allow the Authority to provide good working conditions at the dam site, a characteristic Morgan wanted to be a hallmark of the TVA organization. In particular, TVA employees worked a total of six 5.5 hour days per week, with three days spent on the construction site, and three days in training programs. The board believed that this work schedule would be infeasible under the typical contractor-bid system stating that "the whole training program depends on the direct handling of the work by the authority."[17]

Although, from the onset, engineers familiar with both approaches were in support of using force account methods at TVA, evidence that this approach reduced costs, time or enhanced design flexibility and innovation is limited. In 1937, A.J. Ackerman, the head construction plant engineer, acknowledged that "design costs are way out of line," and that there were "possibilities for introducing economies."[18] Total design costs at TVA dams, as a percentage of total structural cost, range from 2.2% at Wheeler to 6.8% at Hiwassee. The two dams designed entirely by TVA forces (Pickwick Landing and Guntersville) had higher design costs than Norris and Wheeler, both of which were designed by the Bureau of Reclamation. Although Wheeler Dam probably had low design costs because the strong foundation material allowed the Bureau of Reclamation to use a particularly repetitive design, the total design cost for Pickwick Landing, a similar run of the river dam, was twice that of Wheeler. Moreover, Hiwassee, the first tributary dam constructed after Norris, also had markedly higher design costs than either Norris Dam or Tygart Dam in West Virginia, a tributary dam constructed by the Corps of Engineers on the Monongahela River. (Interestingly, the Tygart project drew upon the Corps of Engineers proposed Cove Creek design .[19]) It is worth noting, however, that despite the big difference in design costs, total structural costs were similar among all the dams.[20]

TVA engineers and administration attributed the large design costs in part to the TVA's young organization and lack of engineering experience. By the 1930s, the Bureau had a standardized routine that lowered their design costs, whereas TVA had none of their own design experience to build on. Perhaps even more importantly, the force account method uniquely employed by TVA may have increased the design costs, while reducing the overall cost of construction, reflecting the mantra that, "With force account work, it is generally possible to apply the principle of spending another dollar to save two dollars."[21] While other dam building agencies were unable to modify the design significantly after contractor bidding, the TVA design team worked with the field engineers and construction team to make modifications as each project progressed. Justifying the large design costs to the Board of Directors, Carl Bock (Morgan's assistant chief of the engineering and construction divisions) said, "it is our considered policy to scrap designs and make them over when by so doing a better construction will result or when substantial sums can be saved on construction operation."[22] To demonstrate these overall savings, the engineering department completed a detailed study of design changes and resulting economies for Norris Dam. As construction work progressed and more knowledge about the Norris site became available, engineers altered the diversion scheme to use spillway blocks rather than diversion tubes, eliminated the need for needle valve outlet conduits to regulate outflow, redesigned and moved the powerhouse, and removed a cutoff trench at the heel of the dam. Each of these changes increased the design costs, but resulted in estimated total savings of $980,335, a remarkable result considering the $561,248 total design price tag.[23] Similar TVA studies also showed significant savings from redesign, facilitated by the force account method, at Pickwick Landing, Guntersville and Chickamauga Dams.[24] In addition, there may have been savings at the later TVA dams that resulted from having already designed and built the earlier dams.

Two more points bear further discussion. First, the effect of the force account method on the time required to design and construct the dams is unclear. Although force account construction eliminated some of the delay in contracting and other paperwork, some TVA dams took longer to construct in part because of design changes. Second, despite the flexibility afforded to design engineers through the force account method, there does not appear to have been serious consideration within TVA to think beyond conventional straight-crested concrete gravity dams to examine, for example, concrete buttress dam technology or other more unique or less conservative forms.[25] In fact, it appears that the TVA did little to innovate in terms of form-making (its concrete gravity designs were conservative in terms of dimensions), instead focusing cost-saving efforts on construction techniques.

Recruitment of Engineers

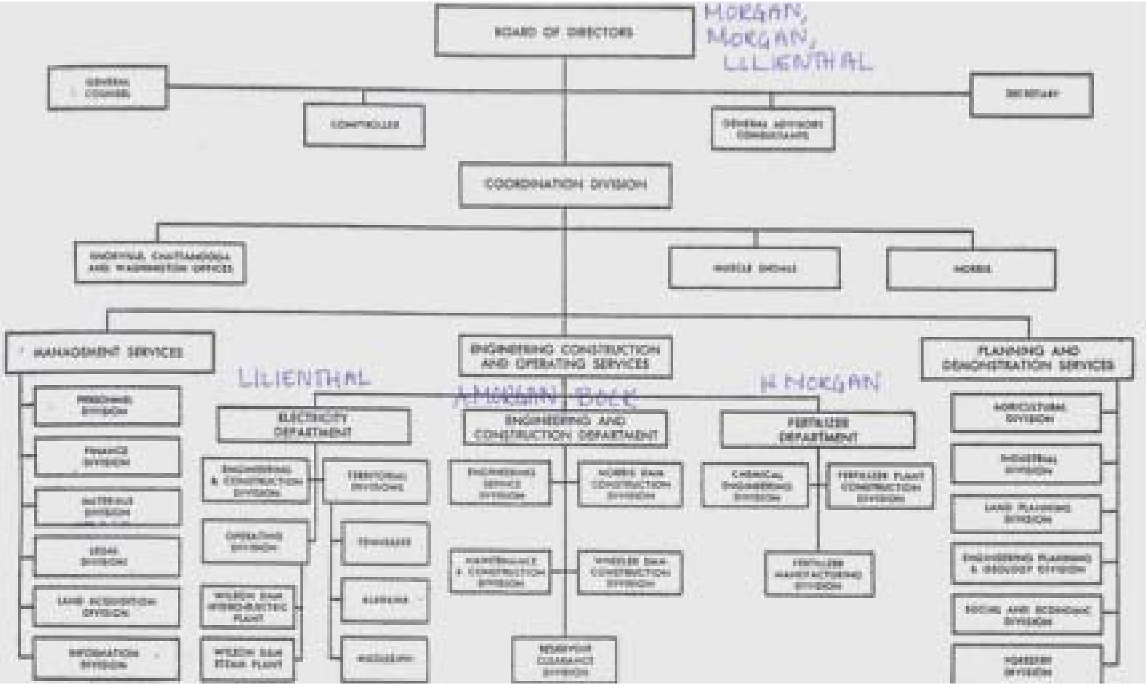
One of TVA's primary challenges during its early years was to recruit a team of engineers with the expertise and know-how to implement the vision that President Roosevelt, Arthur Morgan and the Board of Directors had for the new Authority.[26] Of necessity, hiring and recruitment happened quickly to develop the engineering organization, as shown in Figure 3.

The TVA accomplished this massive buildup in workforce and expertise in part by recruiting a number of engineers and workers with previous dam-building experience with the U.S. Army Corps of Engineers or the Bureau of Reclamation. Theodore Parker, chief construction engineer, and Nicholls Bowden, hydraulic engineer, had both worked on large hydraulic projects with the Corps of Engineers. Byrum Steele and Robert Moore were former Bureau of Reclamation employees; in particular, Steele had worked on Hoover Dam.[27] Moore had previously served as the Senior Engineer in Charge of Structural and Hydraulic Design for the Bureau of Reclamation and played a major role in that organization's designs for Norris and Wheeler Dams.

Crucially, Morgan also drew upon his personal and professional connections to staff the TVA's cadre of engineers. Barton Jones, who eventually became TVA's chief design engineer, had worked with Morgan at the Morgan Engineering Company, the Miami Conservancy, and Antioch College. Morgan had also previously employed other high-level TVA engineers, including Carl Bock, Sherman Woodward, Ross Riegel, Ned Sayford, James Bowman, and Emerson Chandler. In addition, Morgan recruited Dudley Dawson, head of training, from among the faculty at Antioch College. Morgan himself acknowledged the important legacy of

Figure 3

Early TVA organizational chart (dated September, 1934), found in TVA Archives (annotations are mine).



which, unlike most private corporations, was responsible for both the overall vision for the organization and for overseeing a particular aspect of day-to-day operations (see Figure 3). Facing these dual responsibilities, directors did not have adequate time to address both the administrative and the operational issues. John Blandford, Arthur Morgan's secretary, and, later, TVA's general manager, observed: "In reality, there was no board then in existence. Officials had to catch each director severally by his coat tails and get the necessary documents signed."[30] In addition, separation between the three directors allowed each to hire based on personal relationships. This intense interest in specific projects and people, as well as personality clashes amongst the board members, significantly decreased the effectiveness of the tri-section of the organization, representing a failure of leadership.[31] On an undated organizational chart, Carl Bock wrote, "Mature consideration indicates the desirability of having the Directors retire from the administration of those phases of the TVA program which they collectively delegated themselves as individual directors back in the fall of 1933," i.e. their day to day operational responsibilities.[32]

Although much of the squabbling was limited to the Board of Directors, bureaucracy and red tape led to a loss of morale that permeated all levels of the organization. Those employees who

Miami and his employees there, writing, "The general plan of the river control of the TVA and the dam building and administrative organization there was largely the work of men trained on the Miami Conservancy Project."[28] Morgan's selection of these individuals seems to have been largely carried out in the spirit of his professional ethos rather than political patronage, although there were at least a couple of examples of hiring based on political expediency (Morgan hired a disabled friend of Eleanor Roosevelt's; Lilienthal hired the nephew of one of Tennessee's congressional representation).[29]

Organizational Challenges

A number of broader organizational difficulties affected the development of the engineering team. One particular problem was the organization of the Board of Directors between 1933 and 1936 reported directly to the Board of Directors complained of time wasted on bureaucratic and administrative decisions. Bock wrote, "These problems require more than half my own time and energy to combat... They are likewise sapping the energy of heads of our engineering departments, and this … creates a serious situation." The bureaucratic problems, Bock believed, were not a result of the people hired, but rather the organizational system that had developed.[33] Engineering managers also reported hiring difficulties as the public gained knowledge of the organizational issues and conflicts among the Board of Directors: "Recent contacts with high grade prospects for key position invariably elicit questions as to the probable effect of … [the Board's] split on the candidate's situation."[34] Concerns about morale at all levels also inhibited the adoption of suggestions for reorganization, as the administration believed they would further worsen the situation.[35]

The personnel department's bureaucratic hiring process and unpopular salary policy made it difficult for the engineering organization to maintain and hire the necessary staff.[36] The chief design engineer, Steele, observed, "There were many difficulties in building up the design force to adequate strength to handle the work under consideration. These difficulties, however, have increased rather than decreased, due to the bureaucratic procedure established by the Personnel Department."[37] An unsolicited memo on suggestions for improvement written by the senior members of the engineering staff described the personnel department as one of their most significant problems.[38] In addition, exit interviews conducted when employees left the organization indicated that engineers felt that the aim of the salary policy was to "throttle their opportunities with TVA."[39] A 1937 report in Engineering News Record that private engineering hires had increased, only exacerbated concern within TVA leadership about their ability to hire the best engineers.[40]

On an undated organizational chart from the mid-1930s, Carl Bock noted, "the authority is slowly changing from a planning and construction agency to a construction and operating agency."[41] He also acknowledged, "It was fundamentally impossible to design a suitable organization at the beginning because there had been no precedent for an enterprise such as the TVA. With the benefit of actual experience it should now be possible to introduce desirable forms of reorganization and this ought to be accomplished to the fullest extent possible."[42] In particular, the organization could learn from the design and construction experience at Norris and Wheeler dams. These changes in function of the authority led to a major reshuffling of the TVA organization after 1936. One of the critical changes was the institution of the office of general manager to oversee the day-to-day running of the TVA.

Development of an Engineer

During the summer of 2000 and the following academic year, as I worked to document TVA's progress over three years from an organization with a single chairman to a major dam building organization, I strove to develop the research skills needed to accomplish this research successfully. Studies of undergraduates who participate in research have shown that these research experiences help students learn to ask probing questions, solve problems creatively and independently, improve data analysis and analytical skills, and write and communicate clearly.[43]

Research Skills

For me, the TVA research forced me in particular to sharpen my critical thinking skills and improve my ability to formulate research questions. Perhaps Professor Billington, like TVA's Arthur Morgan was "willing to endure a limited amount of confusion in order to give freer play to loyalty, initiative and enthusiasm,"[44] because I credit Professor Billington with patiently putting up with a bit of chaos as I enthusiastically floundered, hoping to hit on something interesting. I spent countless hours sifting through copies of Engineering News-Record from the 1930s, seeking any mention of TVA, and recreating design calculations for Norris Dam to match the design stresses provided on the dam's plans. I learned to follow up on off-hand mentions of people or design antecedents, to see if the details would prove interesting. I remember searching extensively for information about the Bureau of Reclamation's design for Madden Dam, in the Panama Canal region, to try to understand how closely they had followed this design in developing plans for TVA for Norris Dam. Professor Billington made many suggestions, and became excited when I uncovered a new piece of information that would help us chart TVA's trajectory, but he never questioned the fruitfulness of the avenues I chose to pursue. In this way, I learned both how to ask questions ("Who made that decision?" "Why did they make that particular decision?" "Did that person have some previous experiences that affected their decision?") that might open new lines of inquiry, while also learning how to use primary sources, secondary sources, and my own engineering hand-calculations to try to answer these questions. Over time, I began to share Professor Billington's love of the chase of new information. How can you read a description like F.X. Reynolds' (in regards to the TVA Board of Directors) that "disagreement was not taken kindly, and irritations caused reprisals and hindrances, and, they tended to deny to each other the things to which each was entitled,"[45] without wanting to know the backstory and understand how these disagreements affected the organization they led?

Professor Billington's guidance and the TVA research also helped me to see the value in integration of different ideas from the various branches of engineering, and even other disciplines, and the multifaceted demands that engineering makes on its practitioners. As I read about TVA during the 1930s, I learned that some of the challenges the young organization faced resulted from a lack of integration between different engineering branches and the construction organization. For example, engineers complained that while the engineering division determined power capacity at dams, the electrical engineers (housed in the commercial electricity department) designed the transmission lines, often without consulting each other, leading to repeated work once conflicts were discovered.[46] The separation between the design department and the operating division also led to operational inefficiencies when for example, the engineers designed Norris to be operated by twelve people, but twenty-eight men were on site.[47]

Accordingly, our retelling the story of the TVA engineering organization required me to do more than understand the dam's structural engineering design. When I began the project, I was not very knowledgeable about hydroelectric turbine design or electricity transmission, but these were important considerations in dam and powerhouse design. In addition, many of the early engineering decisions were not made for technical reasons at all, but political reasons. I read a number of New Deal and TVA histories to try to better understand these pressures on TVA during the 1930s. In the process, I became fascinated by the role of TVA engineering and engineers within the broader sociopolitical context of TVA and the economic development of the Tennessee Valley. Professor Billington encouraged me to develop a relationship with Professor Jameson Doig of Princeton's Woodrow Wilson School and Political Science Department, and, eventually, to earn a certificate in the Woodrow Wilson School. The interplay between engineering and policy-making and the broader role of engineering in society is something I have come back to in my research repeatedly over the years, a path I set out on because of the TVA research and Professor Billington's encouragement.

I cannot reflect on my experiences researching TVA as an undergraduate without thinking about how much I learned about organizing my research, and writing and communicating clearly. Professor Billington and I met weekly, and sometimes more frequently. At each meeting, I presented what I had accomplished or discovered. Although I don't remember him ever telling me anything like, "Bring me a written summary of what you have done to each meeting," I do know that I got that message. If I look at the folder labeled "TVA" on my computer today, I see typed up notes for each meeting, listing how I spent my time and what I had learned. I created spreadsheets and tables with neatly labeled headings and rows because I wanted to be able to communicate them to Professor Billington at our meetings. I was encouraged write often, and I started trying to articulate – in writing – the goals and findings of our study even before we had made much progress. This process of research and writing, with constant feedback, pushed me to improve my written and oral communication skills.

Mentorship

Almost every study of the value of undergraduate research describes the importance of the relationships that may develop between the undergraduate student and a faculty research mentor.[48] For example, a survey of University of Delaware alumni found that one of the primary reasons students describe their research experiences as positive is the close interaction with their faculty advisor.[49] Another survey of UC Davis students found that the time faculty members spent with students was highly correlated with student satisfaction.[50] These sentiments certainly ring true for me.

As we worked together researching TVA (Figure 4), Professor Billington became my mentor: a teacher, advisor, advocate and friend. I have already described some of the many things he taught me about research, and much of what I know about the great structural designers, dams, bridges, and structural analysis, I learned from him. In addition, Professor Billington remains someone to whom I turn for advice. For the last ten years, I have sought his counsel for the most significant decisions I've made: to seek out a Marshall Scholarship to study in the U.K., to attend Stanford for graduate school, and to start my professional life at the University of Colorado. I have always felt that Professor Billington is my advocate, whether I asked him to be or not. Perhaps most importantly, as we spent all those hours together trying to understand what had happened at TVA, I came to see him as a close friend. Even as we were discussing how important the personal narratives of individual TVA engineers were to the decisions and trajectory of the TVA organization, he made it clear that he cared about my happiness in my personal, as well as professional, life.

I believe I was particularly lucky in having Professor Billington as my first research advisor and mentor, but I am convinced that for many undergraduate researchers the relationship between research student and adviser is a powerful one that remains important long after the research itself has been created. At Princeton, where most undergraduates are required to complete an independent senior thesis project, many of my friends maintain connections with their research advisors. For me, Professor Billington's mentorship had the influence of increasing my own confidence in myself. A number of studies[51,52] have suggested that undergraduate research experiences can help students, and especially women, become more confident in themselves and their intellectual abilities. I know I left Princeton more intellectually confident than I arrived and excited about my chosen professional path.

Conclusions

The human capital and technical expertise built at TVA during its earliest years set the stage for the organization's eventual evolution to a major player in river basin development and power production. In the mid-1930s, TVA's organization seems to have complicated efforts to collaborate across different branches of the organization and to integrate the different components of dam design (civil, mechanical, electrical and chemical). Nevertheless, TVA adopted a design-build approach, probably facilitating the introduction of certain design changes and unique engineering features late in the dam design process and, at the same time, providing design engineers with the flexibility to cope with some of the organizational and communication challenges they faced. During the later part of the 1930s, modifications were made to remedy the problematic organizational structure and to try to bring design costs more under control.

Similar to TVA, I started my own research by enlisting a lot of help, but as time progressed, my research skills and confidence increased and I increasingly began to chart my own path. For my senior thesis at Princeton, I researched engineering innovations at Bonneville Dam, close to my hometown of Portland, Oregon. I chose to go to graduate school, encouraged by both Professor Billington and my positive experiences researching TVA. In fact, working with Professor Billington researching TVA's early days has influenced almost every aspect of what I do today as an Assistant Professor at the University of Colorado, Boulder. Although my research is now focused primarily on disaster-resistant design

Figure 4

The author, with Professor David Billington, at the Princeton University P-Rade (2002).

and construction, a significant part of my scholarship involves thinking about how public policy, politics and individual decisions influence technical decisions (for example deciding whether or not to seismically retrofit my home) and vice versa. In the classroom, I use the lessons learned from TVA and from thinking critically about seismically vulnerable buildings to develop case studies and stories of civil engineering successes and failures. These stories provide powerful tools for teaching students about the economic, societal and political impacts that affect any major engineering effort. These lessons can help our students better understand and navigate engineering design processes, including technical considerations of economy and efficiency and human considerations.

Whenever possible, I engage undergraduates in my research endeavors. If they benefit half as much as I did, it is time well spent.

Acknowledgments

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STRUCTURAL ART IN CONTEMPORARY ENGINEERING EDUCATION

Sinéad C. Mac Namara

Introduction

Structural Art has a pivotal role to play in the future of engineering education. Contemporary engineering education research is concerned with a host of issues that impact not just recruitment and retention of talented young engineers, but also the nature and quality of the skills and knowledge that those students will bring to the workforce or further study. Among the primary concerns are: student capacity to engage in big-picture, holistic, systems level thinking; creativity and innovation in problem solving and design; and recruitment and retention of women and minorities. The study of structural art is uniquely placed to address a number of these concerns in the education of young structural engineers.

I had the privilege of working for David Billington for six years as a teaching assistant. I came from a traditional structural engineering undergraduate education and was astounded, delighted, and energized to discover that all the technical knowledge I had acquired had a purpose, value and meaning, far beyond the boundary conditions I had been taught to believe were in place. I arrived in Princeton from Dublin on July 3rd 2000 and was promptly dispatched to Knoxville, Tennessee to the archives of the Tennessee Valley Authority. Abbie Liel and I spent the next few days searching through the telegrams between President Roosevelt and engineers Morgan and Lilienthal sent during the early months of the TVA. What followed was for me a crash course in American history, geography, politics and engineering. Nothing in my education so far had inspired me to think about the relationship between those things. It was in these days that I began to fully understand what an engineer is, and the role my discipline plays in what our world looks like, how it functions, and how it evolves. In learning and beginning to teach structural art, I was attracted first to the fundamental knowledge itself. Why had no one ever told me what a bending moment diagram was for? I was suddenly allowed to care about art? Different political environments produce different kinds of structures? This was revolutionary stuff! But I also saw the enthusiasm for engineering that this approach engenders in students, even non-technical students. Through my own teaching and research, I become ever more convinced that Structural Art is a vital part of the structural engineer's education, and that broad dissemination of this discourse can contribute to the solution of many pressing issues in engineering education.

Below is a discussion of the potential of structural art to address some of the primary concerns of contemporary engineering education researchers, and a brief description of some of my own attempts to infuse my teaching to architects and civil engineers at Syracuse with structural art.

Engineering Education Research and Structural Art

Among the primary concerns in contemporary engineering education research are: problem based learning to address the piecemeal nature of traditional engineering learning; students' lack of exposure to the real world problems of their discipline; creativity in engineering education; design in engineering education; and diversity of the engineering student body. In structural engineering education, structural art represents a rich opportunity to address each of these problems in turn.

Big Picture Thinking aka Problem Based Learning

There is much discussion in engineering education literature about the appropriateness of current methods in preparing students to work independently, to solve unfamiliar problems, and to engage in systems level thinking. Students of structural engineering in traditional programs that do not teach structural art are very rarely exposed either to real structures and engineers, or to the whole structure as an object in itself as opposed to a series of components. In the National Academy of Science's report *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, a fundamental source document in engineering education research, Linda Katehi laments the common engineering teaching paradigm that divides complex problems into many pieces which students are then taught to solve independently, all the while anticipating that eventually, they will

> "be able to develop a solution by combining them… Eventually...the effort involved in learning about the small pieces is so overwhelming that we can no longer synthesize the original problem–the parts become more important than the whole."[1]

This engineering curricular focus on solving one problem at a time assuming a singular answer or solution, stands in direct contrast to "the history of modern technology and society in all its vital messy complexity."[2] As Charles Vest, former President of MIT writes in the same report, "There are two frontiers of engineering" and "each is associated with increasing complexity."[3] Problem based learning is widely proposed as the optimal solution to this issue. An educational method used across disciplines, problem based learning is closer to the real practice of engineering than traditional engineering education. It requires students to act as professionals to solve a real world problem without fully defined boundary conditions or sufficient information. The study of structural art can better prepare students to engage in problem based learning as it models the problem solving of professional engineers and particularly because it exposes the students to the most creative examples of innovation and evolution of structural form in response to new materials, longer spans, and taller buildings.

Structural Engineering Students' Understanding of their Discipline

In a series of formal and informal surveys of Syracuse University engineering students, I have found students in the middle of their engineering education to be very unfamiliar with the practice of engineering. The most surprising thing about the surveys described here is that no one in engineering or science education is surprised by the results, but educators outside of engineering and science are shocked.

In an informal survey, I asked a lecture hall of over 100 engineering students at the start of their sophomore year to name an engineer whose work they admired. Not a single student was willing to venture an answer. When I further asked them to name any engineer, the group collectively offered up: Nikola Tesla and a handful of names of College of Engineering Faculty.

In a more controlled environment, when carrying out initial evaluation for a cross-disciplinary architecture/engineering seminar (described later in this paper) structural engineering and architecture students answered a survey about their cross-professional perceptions. All students were asked to name three engineers and three architects whose work they found interesting. In two iterations of the course, only five out of twenty four engineering students even attempted the question. Between them they came up with five engineers (Leonardo daVinci, Michelangelo, Thomas Edison, Benjamin Franklin, and Santiago Calatrava). They could actually name more architects. The students were asked to identify three buildings or structures they found aesthetically or architecturally interesting and three they found structurally interesting. The answers to this question were slightly more encouraging. All of the engineering students attempted the question. They were however, much more likely to answer the question with examples of buildings on the SU campus, Las Vegas casinos, and the one or two case studies that upon questioning it was revealed they had encountered in a previous course, rather than with anything we would consider structural art.[4] In discussing these results with the groups each year, I threw out a few names of structures: the Eiffel Tower, the Hoover Dam, the Brooklyn Bridge, the Empire State Building, and mentioned I was surprised that no-one had given those as an answer. The students mostly responded that they never really thought of those objects as belonging to the field of structural engineering, and for that matter that they did not think very much about the structures they encountered daily and how they related to the things that they were learning.

If third year engineering students are ignorant of the canon of historical figures of the discipline, then we as instructors are certainly to blame. But when many appear to have applied to engineering schools, accepted places, and completed five or six semesters of engineering education without much thought as to the things engineers create then it is clear that the discipline has a PR problem. One would be shocked to find an architecture student who did not have a good answer when asked about their favorite buildings or architects, or a law student who could not name a few landmark cases that inspired them, or a medical student who had never really thought about a doctor's role in society, or a music composition scholar who had never heard of Mozart. In fact one might be surprised by such responses from any educated young person regardless of their area of study.

Educating engineers with a broad understanding of what technology can do, and how innovations have occurred in the past has never been more important. The physical infrastructure of this country is aging and the population seems ever less interested in investing in its improvement. Bernard Amadei, founder of Engineers without Borders, notes that we currently do 90% of the world's engineering for 10% of its population.[5] The developing world is undergoing massive and rapid growth while at the same time there is increasing concern for limited resources and environmental impact associated with industrialization. Massive engineering challenges lie ahead for our students. It is imperative that we equip them to solve the engineering problems yet to come. Who better as role models for these students than Telford, a product of the industrial revolution, whose bridges were a tool of an expanding global empire, or Maillart, who refused to be bound by computational limitations when testing new forms for a new material to efficiently and economically serve isolated and poor populations?

Creativity in Engineering Education

Engineering has always been a discipline of innovation and creativity. But engineering education has lost sight of these central values that the pioneers of the discipline so fully personified. In fact, some of engineering's most recent innovators famously did not finish college (Bill Gates, Steve Jobs, and Michael Dell), in part because they did not see the relevance of a normative engineering education to their work and their creative technical passions. There is a common, but mistaken belief that engineering is strictly an applied science. Scientists do the discovering, so this view assumes, and engineers find applications for those discoveries. Even a cursory look at the evolution of modern engineering, however, proves this assumption false. Carnot made many of his first historic strides in the science of thermodynamics by studying the engines of James Watt.[6] The self taught engineers, the Wright brothers, took flight before astrophysicist Samuel Langley began working on behalf of the U.S. Naval Academy and Smithsonian Institute.[7] Navier's groundbreaking *Mémoire sur les Ponts Suspendus* (1823), the earliest significant academic paper on the structural capacity of suspension bridges, is a study of bridges already built, such as Telford's Menai Straits. Telford's Menai Straits bridge was built without the benefit of advanced mathematical design equations. Rather, it was created from design intuition, intimate knowledge of material gained through decades of building experimentation, and observation of full-scale behavior.[8] There is no doubt that both academic and practicing engineers continue to be creative every day in their labs, on their jobsites, and in their workshops and offices, but engineering education does not consistently address this vital skill, few programs address creativity and its relationship to research and design, or explicitly integrate it into an undergraduate student's training.

The ability to see things broadly and without the need for sharp definition (i.e. with ambiguity) is a central tenet of creativity and a highly desirable skill in anyone engaged in high level systems thinking like an engineer. The study of structural art gives lie to the perception that mathematical methods will always provide the one true answer to any engineering problem. It forces students to confront multiple modes of problem definition and problem solution. It teaches them about the way expert engineers have handled ambiguity and uncertainty.

Engineering Design Education

Engineering education researchers and practitioners widely acknowledge the problem of design education in engineering programs. Studies of engineering student design processes report a significant difference between the capacity of student engineers and engineering practitioners in "problem scoping" and "information gathering" at the start of a design project, and argue that engineering students would benefit from teaching methods designed to model that process for them.[9] Studying the true innovators in structural art provides a model for engineering students in problem solving and design. To know how the classic solutions have evolved is as important as knowing how to implement them.

In the 1990s, first-year design courses were widely introduced in engineering programs in an attempt to introduce students to the nature of their chosen profession earlier in their college careers.[10] Dym et al identify a host of institutions that introduced design thinking through project-based learning in their first year programs.[11] Most of these schools reported a positive impact on retention for those students who had taken some form of first year "cornerstone" engineering design course. Dym et al further argue that such courses have a positive impact on student interest and performance in later engineering courses. Following from ABET requirements for a final year design project with "realistic constraints" most programs have instituted a capstone design course and many include some element of industry participation and an attempt to use real world problems.[12] Capstone design courses at the end of engineering programs represent an opportunity for students to take on both design work and a whole real world structure. However, there is a critique that this bookending approach (with cornerstone courses in the first year and capstone in the final year) can create a "valley of despair" in the second and third years and that the benefits of project-based learning are limited when they are not spread throughout the curriculum. A study at the University of Colorado found that student confidence over five categories (Engineering as a Career, Engineering Methods, Design, Communication and Teamwork) actually decreased between the end of first and the end of fourth year.[13] For structural engineering students, the study of structural art could help fill the "valley of despair", exposing students to the very best of their discipline, engendering enthusiasm for their discipline, and creating a context for the knowledge they are learning in their other core required courses such as statics, mechanics of solids and structural analysis.

Education researchers have also found that the stark differences between the highly defined problems encountered in the typical lecture or lab and the more complex, less defined, open-ended projects in capstone present a significant challenge to student success.[14] Similarly, students' relative lack of experience with scoping a design problem makes for a very heavy faculty mentorship load in such courses.[15] For an experience that should be a bridge to their more independent work life, this is an issue of concern. If more structural engineering students were exposed to structural art they would have a set of precedents for structural design to call on for inspiration. They would have a greater understanding of the parameters of an engineering design. Students who had taken a course or courses on structural art would be far better equipped to make decisions about form. They would have some experience considering all the externalities of engineering design that are ignored in a traditional curriculum. In a rush to meet ABET requirements; budgetary constraints, environmental and legislative requirements, aesthetic concerns, etc. suddenly show up on students' plate in their last semester of engineering education. The traditional engineering education spends three and a half years teaching the scientific and then expects students to suddenly engage competently with the social and symbolic aspects of engineering design.

Diversity and Creativity

The role of diversity of student body, a longstanding problem in the STEM fields, in sparking creative ideas and in collaborative innovation is significant. There is evidence that a perceived lack of creativity in engineering is partly to blame for the lack of diversity in applicants to engineering schools. The study of structural art would challenge this misperception.

There is a burgeoning field of educational research that documents the educational and cognitive benefits of diversity.[16, 17, 18] It is argued that "creativity and diversity are linked" and "both are necessary to fully exploit the potential of women to contribute to the science and technology enterprise."[19] Additional research has found that less homogenous teams are more creative,[20,21,22] and that groups of diverse student problem solvers can even outperform groups of expert or high-ability problem solvers."[23] Engineering as a discipline has a special responsibility and opportunity to foster and promote a population of students from diverse educational, cultural, and socio-economic backgrounds. Engineering at universities is widely recognized as a popular major for first generation college students (in contrast to traditionally "creative" disciplines of art, architecture, and writing), and as any student of structural art knows, the history of engineering is full of self-made, self-educated men and women.

It is generally acknowledged that increasing diversity in our student body (diversity of ethnicity, skill set, gender, educational background) fails in part because of the high math and science barriers in the first two years of undergraduate study. However there is also evidence that many students become frustrated by a lack of "big picture" thinking and apparent social relevance, and that women and minority students are more likely cite such reasons for not pursuing engineering.[24] Structural art, encompassing as it does the social, political, and economic facets of engineering, represents a rich opportunity to subvert this paradigm. Anderson and Gilbride's 2005 study of 2,500 Canadian students showed that both male and female students did not think engineering would be an interesting career for women and that 44 percent of males and only 23 percent of women viewed "engineering as an exciting, creative career."[25] Not only do we lose creative students from the fields of engineering, we do not attract them in the first place, by failing to impress upon diverse students that engineering is a creative endeavor. Increased awareness of structural art and a prominent place for such study in curriculum has very real potential to attract a more diverse student body to civil engineering.

Educational Experiments in Structural Art

In teaching structures to engineers and architects at Syracuse I have developed two courses that explicitly use structural art. The first is an introductory structures course for architecture students and the second is a cross-disciplinary architecture and engineering design course. These courses provide examples of the applicability of structural art in teaching structures to both engineering and non-engineering audiences.

Structures I

In the role of project manager and creative director, the architect needs to successfully engage with experts in multiple areas of engineering. To this end, a solid grasp of the fundamentals of structural engineering is vital. An intuitive understanding of structural engineering grounded in real world examples is vital to inculcate structural innovation in architecture students' future work. Teaching structural art is an extraordinarily powerful way to do this. It provides a framework for how structural innovation has happened in the past and a presents a rubric for how bowing to the physical forces at play and activating the capacity of the material in question can lead to efficiency and elegance of form.

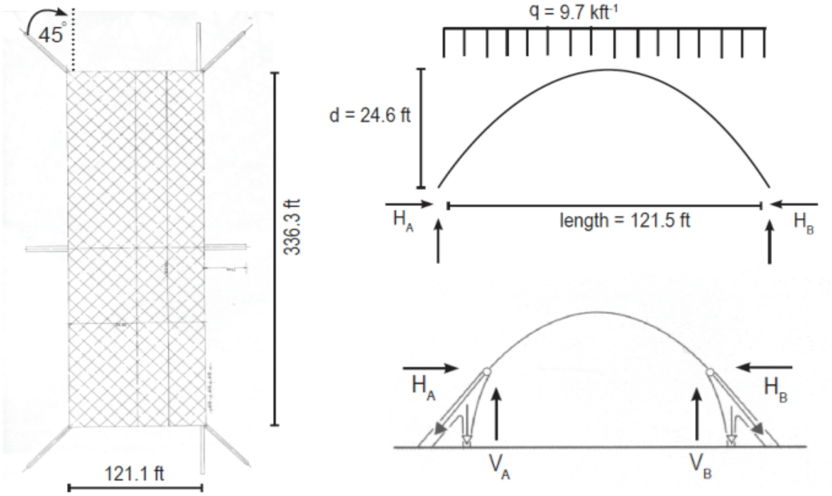
Structures I, is the first of a two-course sequence in structures required for all students in both the BArch and MArch first professional degree programs at Syracuse University School of Architecture. As per the accreditation requirements, the course introduces basic concepts of structural system behavior; gravity and lateral loads, analysis of major structural forms, and structural performance of materials. Structural art forms the basis of this course. Examples of the very best of structural engineering, those structures that embody the principles of efficiency, economy and elegance make for the best teaching examples when the aim is

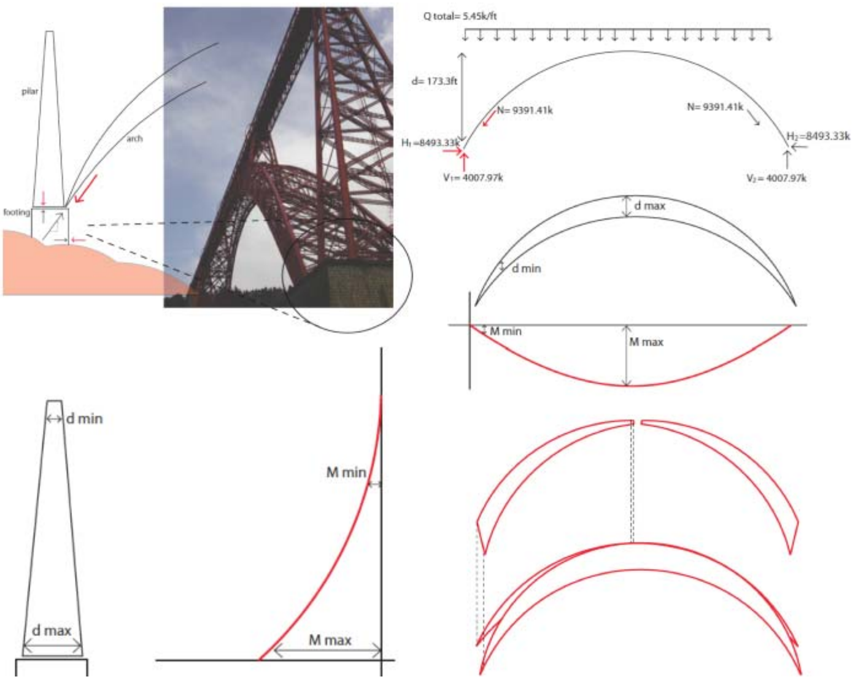
Figure 1

Student case study analysis of the Orvieto Hangar, designed by Pier Luigi Nervi, 1935 [Vijaya Diana Pieterson, Syracuse University School of Architecture].

Figure 2

Student case study analysis of the Garabit Viaduct designed by Gustav Eiffel, 1855 [Lindsay Woodson and Jose Arango, Syracuse University School of Architecture].





to generate an appreciation for the role of structure in architecture and design.

The teaching of structures is often viewed as marginal in the overall architecture curriculum. A search of JAE archives produces very few articles devoted to the subject. My senior colleagues in architecture anecdotally report that they have seen the number (and level of complexity) of required structures courses decline over the course of their teaching careers. I regularly survey the students on the first day of their first structures course and less than 30% say they would take the course if it were not required. However, by the time the students are at the end of the first semester, their attitudes have changed considerably, and I attribute this to the fact that the course is about structural art. Studying structural art fosters a deeper understanding of the role of structure in architecture. Structural art presents those structures that represent the very best and most innovative examples of structural form and material use. These case studies that are most illustrative of structural art emerged as engineers strove to find new forms for new industrialized materials and to span ever wider and build ever taller.

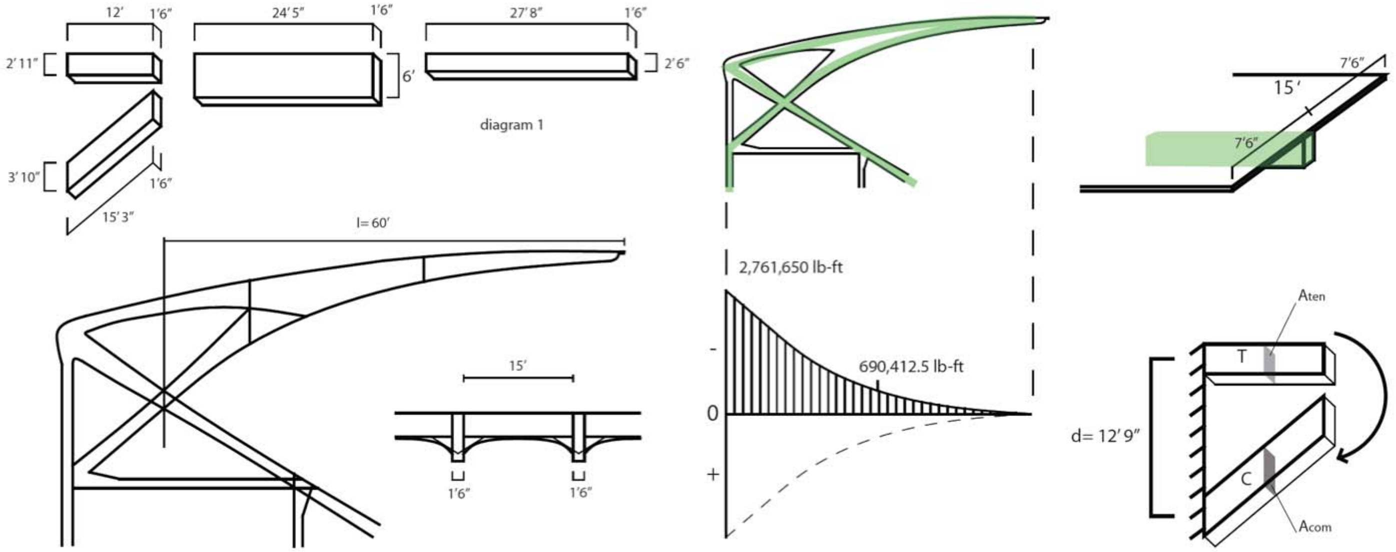
A series of lectures introduce new topics in the structures curriculum through examples of structural art. The course is very closely modeled on David Billington's Structures in the Urban Environment course at Princeton. The study of Thomas Telford's iron bridges introduces the mathematics of the cable and the arch and the importance of new forms for new materials. The Eiffel Tower is an object lesson in the importance and relevance of the dreaded bending moment diagram. The George Washington Bridge repre-

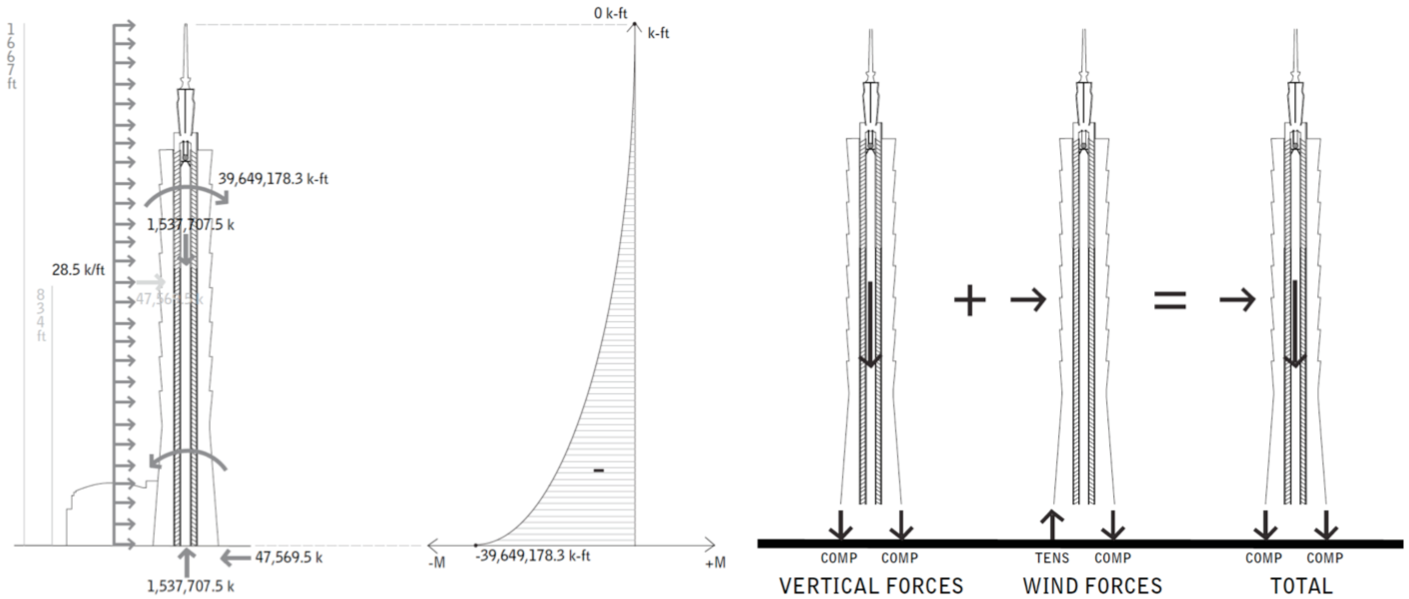
Figure 3

Student case study analysis of the Florence Stadium designed by Pier Luigi Nervi, 1931 [Karen Kentile, Syracuse University School of Architecture].

Figure 4

Student case study analysis of Taipei 101 designed by C.Y. Lee and Partners, Thornton-Tomasetti Engineers, 2003 [Elizabeth Mikula, Molly Poes and Christopher DePalma, Syracuse University School of Architecture].





sents an opportunity to talk about safety and load probability calculations. Discussing Fazlur Kahn at SOM working on the first tube buildings with Bruce Graham (the Hancock Tower, the Sears Tower) serves as both an introduction to the most widely used forms for tall buildings but also into how the architect/engineer relationship can have a synergy that creates something entirely new that neither discipline would likely produce in isolation. The bridges of Robert Maillart are a favorite among architecture students and illustrate the nature of concrete, the evolution of structural form to match and to manipulate the forces resulting from the loads on the structure. Shells and plates are very difficult to understand mathematically, and are generally only covered in graduate level courses for engineers. But, Pier Luigi Nervi's ribbed domes, slabs, and barrel vaults are so structurally expressive with the ribs articulating the flow of the forces, that any student can gain an appreciation for the potential of such forms. The inverted hanging forms of Gaudi and Heinz Isler are similarly accessible in principle despite their complexity in detail. The students all build their own shell models, and test them to failure, using the methodologies of Gaudi and Isler. Seeing the historical form finding methodologies of someone like Gaudi, who is familiar to them from their architectural history courses, and understanding how concerned he was with efficient load carrying (like the Gothic stonemasons before him) is an eye opening moment for architecture students who do not see structures as integral to their design agenda. Taking a 2 ft x 3 ft piece of canvas and some rockite, and making a shell only millimeters thick, and then finding that it can hold the weight of one of their team members, is an object lesson in the power of the curve and the potential of appropriate structural form that students remember years after they take the course. The work of Torroja and Candela provide insight into how a properly designed shell can in one simple move provide structure, enclosure, aperture and façade.

The students in the course also undertake a case study of their own at the end of the semester Although being asked to write in a structures course often surprises students, the idea of precedent study is familiar to them. Precedent study and historical analyses are modes of pedagogy that are familiar to architecture students, but an independent mathematically analysis is not something they have attempted before. Ultimately almost all students produce a reasonable mathematical analysis of their chosen structure, but more importantly all can demonstrate diagrammatically how the principal load carrying mechanism functions. Some of the student analyses are shown in Figures 1-4.

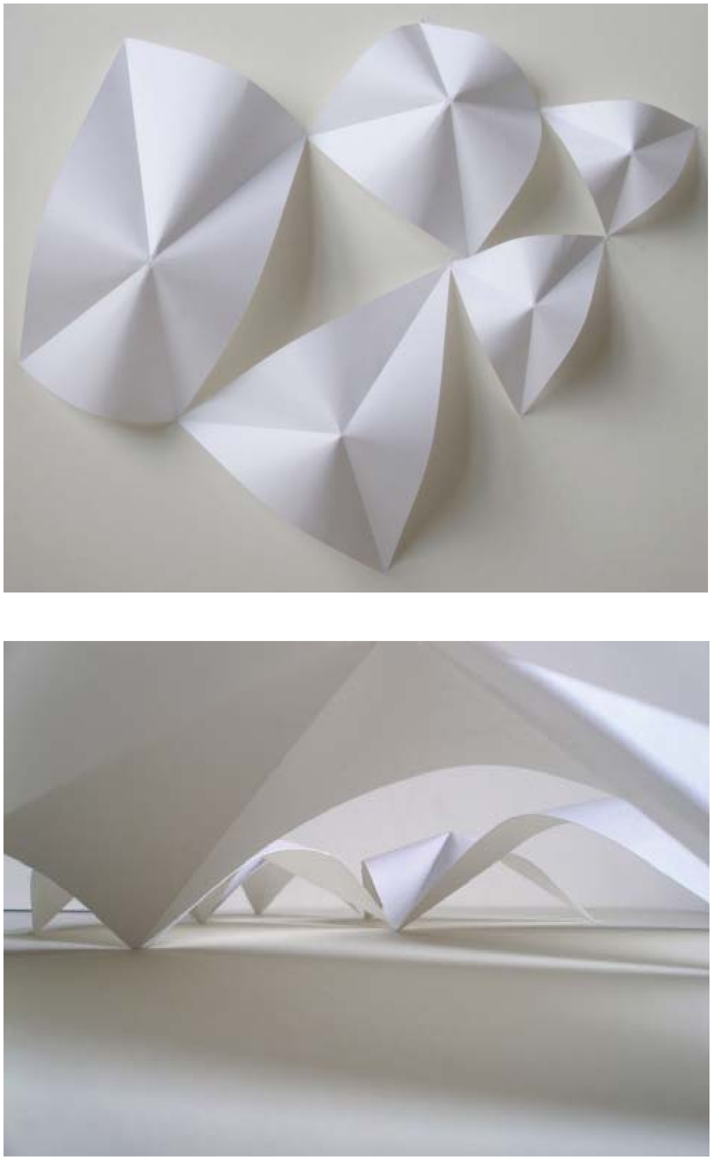
The response of students to structural art has been overwhelmingly positive. In five years of teaching the introductory structures course this way at Syracuse University School of Architecture the students have shown considerable enthusiasm both for the structural art but also for further structural research. Between 25% and 30% of the graduating class request a structural consult on their thesis design project, this was not so before the course was taught as described here.

In order to gather more formal student response data a survey was sent to approximately 350 students who have taken the course over the last three years (those from four years ago having graduated). The response rate was 127 students within three days. The group had a mix of bachelors and masters students and a ratio of men to women that was similar to that of the total population who had taken the course. The size and make-up of the response group lends considerable weight to the validity of the responses.

Student reactions to the examples of structural art used in Structures I to introduce fundamental structural principles in the survey show broad based support for this approach. A concern when using analysis of real structures with novice structures students is that it may be unnecessarily complex and cloud the students understanding of the underlying principle. On average, students did not share this concern and over 75% of students disagreed that abstract textbook examples would be easier to digest. Far from being put off by the structural art examples, students seemed to think it was the obvious way to approach learning structures with over 90% of students in agreement or strong agreement with that statement. This revelation is perhaps not sur-

Figure 5

Shells Trans-disciplinary Design Seminar: Paper Parabolas.



prising to those in architecture education where history surveys are an absolute pre-requisite, but to engineering educators it is almost revolutionary. The most encouraging results from the survey were that students felt the study of structural had value both in learning the new concepts and in appreciating how those concepts were useful and relevant in their own work. Approximately 90% of survey respondents either agreed or strongly agreed that historical case studies made it easier to understand the course material and facilitated a deeper appreciation of the role of structural engineering in architecture. Furthermore, 60% agreed or strongly agreed that this approach made them more confident in applying their new knowledge in the studio. Thus, the value of structural art in activating student engagement in both structures and the application to their design work is clear.

The survey respondents were also given an opportunity to add any open-ended comments they might have on the use of structural art in the course. A number of students responded that it was the "reality" of these historical case studies that made them useful pedagogical tools:

> "I enjoyed the use of historical examples because I always find it helpful to look at something real rather than something imagined or just a diagram in a textbook. I think people can visualize it more easily that way."

> "Historical examples kept me interested in what we were learning in class. It helps to see real life applications to the concepts."

> "Memorization is not my strong point. Having a story to attach to the topic we were learning really helped me to remember it."

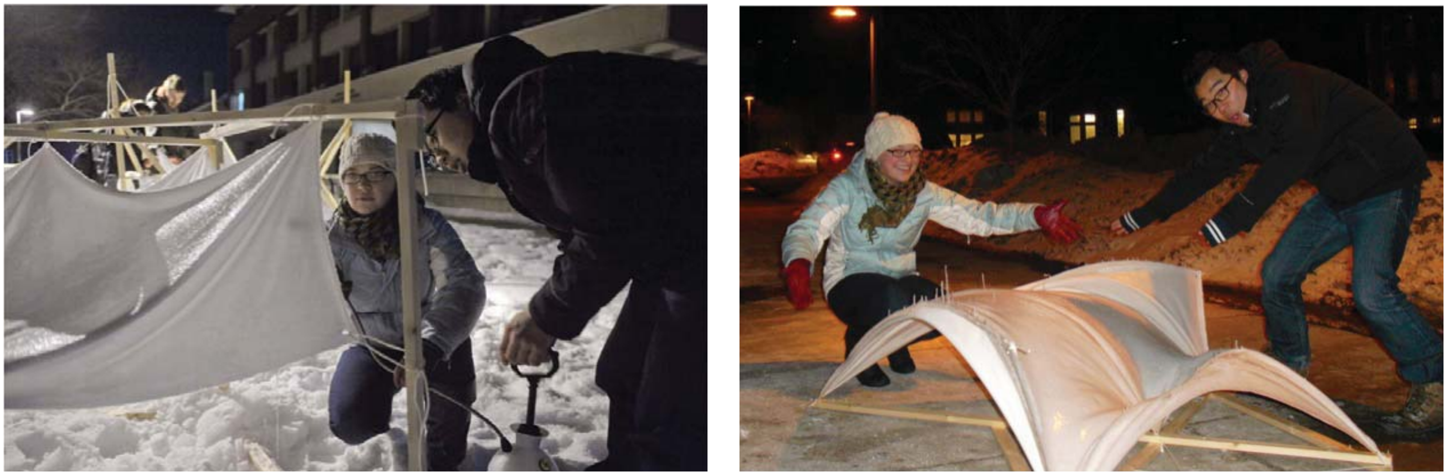
However, they also demonstrated more nuanced interpretations of the role of the examples of structural art, such as the capacity

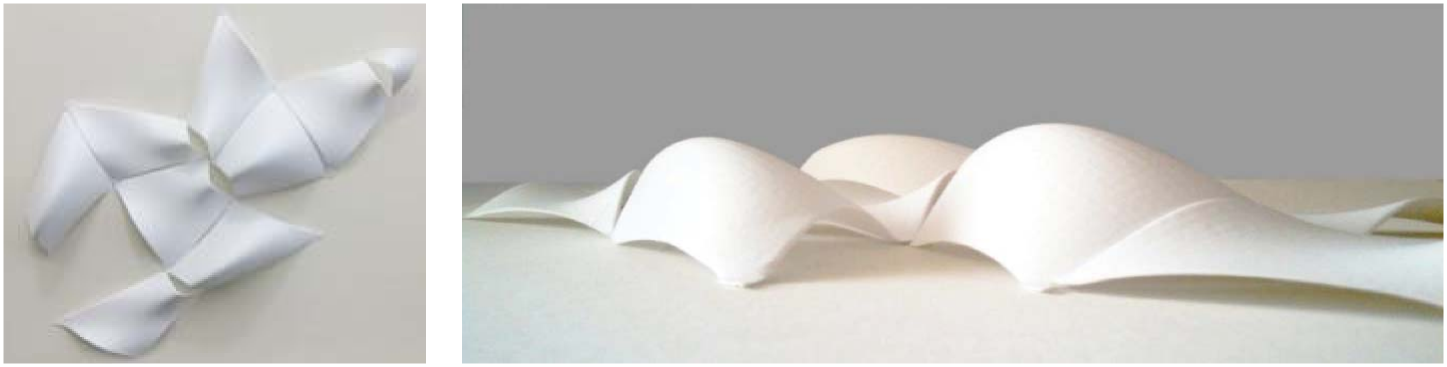
Figure 6

Shells Trans-disciplinary Design Seminar: Frozen Form.
[Stephen F. Satori, Syracuse University Photo and Imaging Center].

Figure 7

Shells Trans-disciplinary Design Seminar: Aggregation and Aperture.





to illuminate the evolution of structural form, which in turn made structural forms easier to understand.

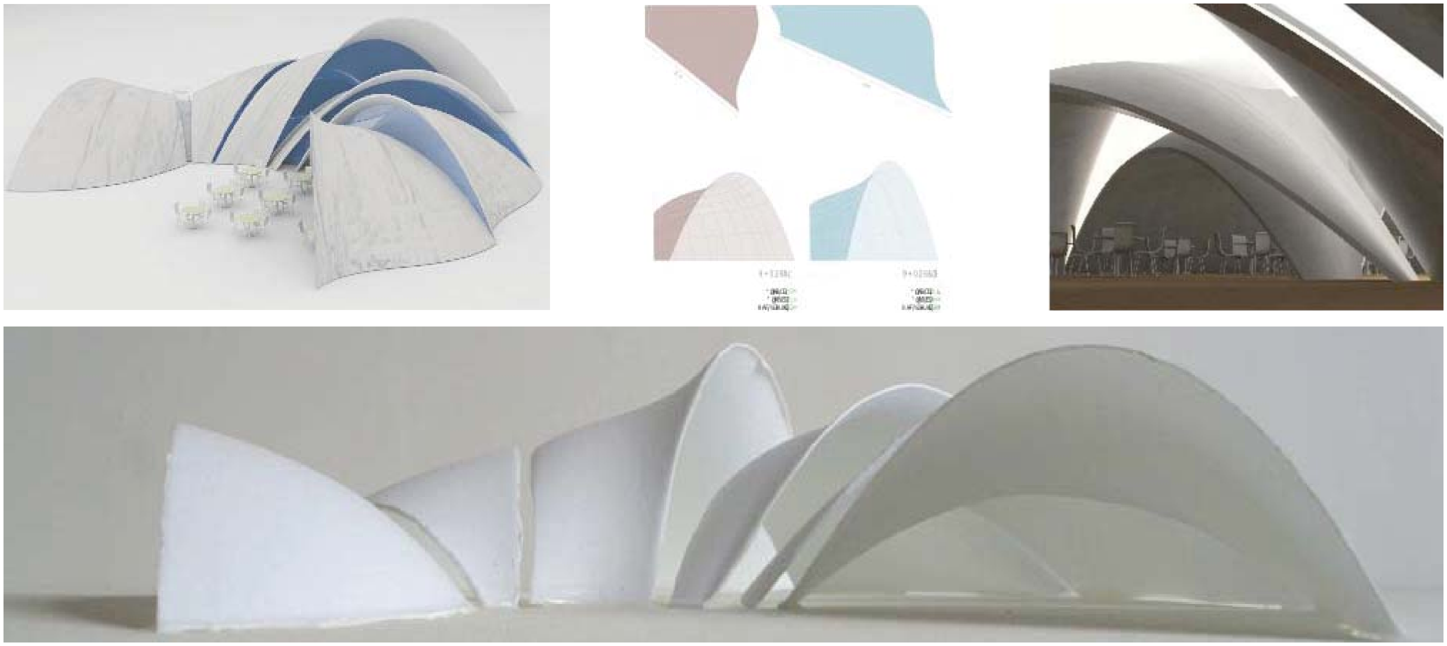
> "I thought using historical examples was a great way to learn about structure and its evolution."

> "I believe that using historical examples of structural systems is very helpful to the learning process; it is important to understand not just modern structural systems, but where they came from and how they evolved into what they are today. Using recognizable historical structures also helps to give context to the examples being used, possibly making the material easier to understand/relate to real-life"

Further, they appreciated the study of individual engineers and engineer/architects and their approach to problem solving and how that might have relevance to their own design work.

Figure 8

Shells Trans-disciplinary Design Seminar: Aggregation and Aperture.



> "I especially liked learning about the structural engineers and how they used simple ideas to manage design problems. It got me thinking that even in our studio projects we could potentially fix certain design problems by simply changing the shape."

There is little discussion of the role of structures in architecture education in the relevant literature. Student enthusiasm, and indeed background knowledge required, to undertake complex mathematics is not high. And yet, contemporary architecture students will graduate into an ever more technologically complex environment in their practice of the discipline. As such, it is vital to give students both an appreciation for the role of structure in design, and the critical skills required to analyze structures. We must equip them for the further study of the subject that will be necessary for those who wish to pursue innovations in the technological aspects of their practice. Structural art is the best method to teach fundamental structural principles and to activate the relationship between history, structure, and design. The student response data is overwhelmingly positive in support of this claim, and the student engagement in the course is very high for a required course of this nature.

Trans-disciplinary Design Seminar: Shell Structures

The trans-disciplinary design seminar (TDS) aims to integrate engineering research into the creative design process. It is an elective course offered to civil engineering and architecture students. The course was intended as an experiment to test if the pedagogy of architecture could be used to foster creativity and innovation in engineering students. As such the course was designed to require open-ended problem solving, resolving competing goals in a complex problem, balancing technical merit against architectural

Figure 9

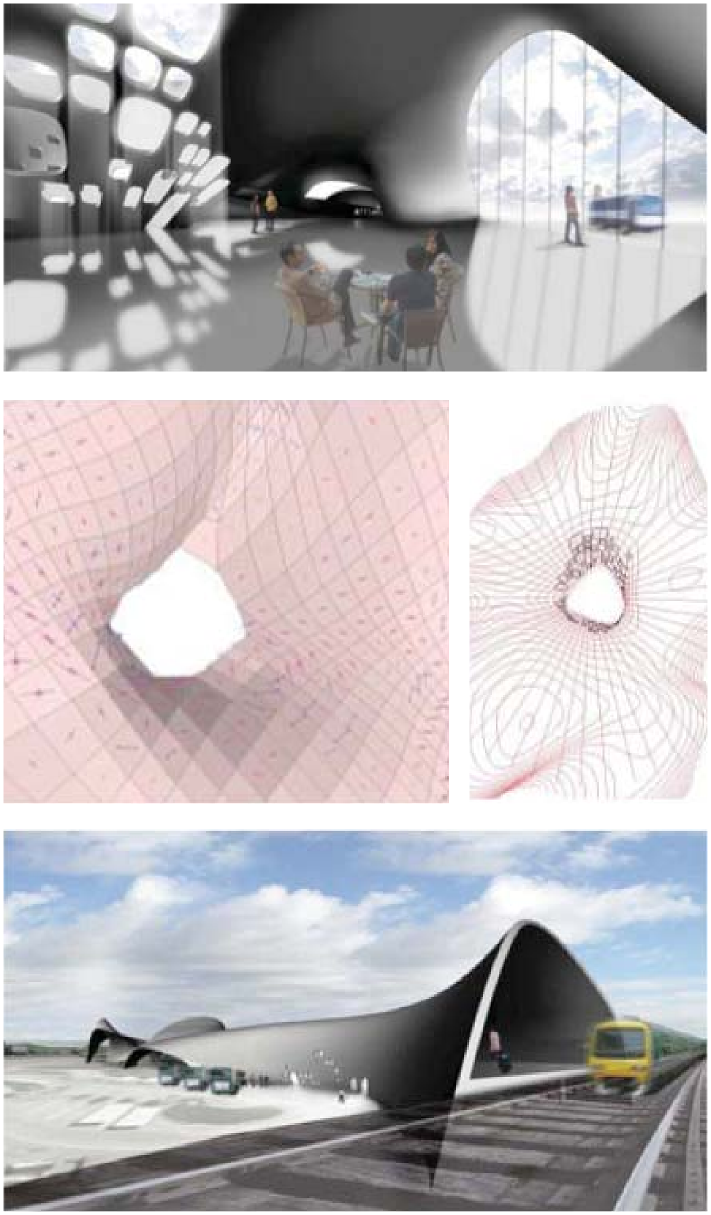
Shells Trans-disciplinary Design Seminar: Final Design Project.

design values, and positing speculative designs. For engineering students, the TDS was an opportunity to experience one-on-one instruction typical of design studios in the architecture. For architecture students this was an opportunity to work with technical constraints in a new way. The course was co taught with an architecture colleague.

Structural art was at the heart of this course as the subject matter was Shell Structures. The students received a number of lectures on the structural artists Candela, Torroja, Nervi and Isler. There were also some lectures on shells and curvilinear form in contemporary architecture such as Toyo Ito's crematorium and the work of Zaha Hadid. The students undertook a series of short design exercises in the first two thirds of the semester. Paper models were built to investigate parabolic form. Out on the quad, funicular fabric models using water (and the reliable Syracuse winter) to create frozen shells in perfect compression ala Heinz Isler, created quite the stir. Students completed a study on modules and their aggregation in the spirit of Felix Candela using milling and

Figure 10

Shells Trans-disciplinary Design Seminar: Final Design Project– Students used FEM analysis of stress paths to orient windows.



vacuum forming technologies. Each group reviewed the technical and architectural literature on an assigned structure and made a precedent analysis presentation. The final design project was to redesign the Regional Transportation Center in Syracuse using a shell structure to incorporate the bus and train station. Students performed a FEM analysis of their proposed shell as part of the design process, and were required to present the both the technical and architectural rationale for their design to final jury of architects and engineers. Examples of some of the models and images produced are shown in Figures 5-10.

The course is a work in progress and the results of the first two iterations are encouraging. Student enthusiasm for the course is high for both groups. The quality of the design work was highly rated by both the teaching faculty and the final project jury. The evaluation team from the SU School of Education has noted considerable buy-in from the students to the concept of cross disciplinary courses and surprising adaptability on the part of engineering students to the broader more open understanding of engineering that comes from studying structural art. Several individual students have ongoing engagement with academic issues they first encountered in the course (thesis projects, independent study, graduate school plans). In exhaustive formal pre and post surveys (not presented here) it was proven that each group of students had generally improved opinions of the other after taking the course. The biggest changes in student disciplinary perceptions were that architects gained technical confidence after taking the course and engineers viewed their profession as more multi-talented, big-picture thinking and considerably more artistic. As the course evolves the primary aims will be to engage the engineering students more deeply in the design process and improve their confidence in creativity and innovation in both their own work and in the wider discipline.

Conclusions

For structural engineering students the study of structural art is extraordinarily important. Understanding what the discipline does, the impact that structural engineers have had on infrastructure, transportation, the way cities and towns look, feel and operate will not just make them better engineers, it will make them better advocates for structural engineering and for technology more generally. Without the study of structural art a structural engineer has a toolbox full of algorithms and subroutines but no idea what any of it is for, no understanding of the immense responsibility and influence their discipline has with regard to how the physical environment that we live in functions. Social, Scientific, Symbolic makes for a nice alliteration, but the simplicity of the phrase belies the complexity at the heart of structural art. It is through the study of the best innovators and innovations of structural engineering that the structural engineering student can come to understand their discipline as a field of knowledge, fundamental to human development, that intertwines at every turn with the fields of art, architecture, politics, history, and economics.

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STRUCTURAL ANALYSIS OF EDUARDO TORROJA'S FRONTÓN DE RECOLETOS' ROOF

Ignacio Payá-Zaforteza and Jose Antonio Lozano-Galant

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Abstract

Eduardo Torroja's thin concrete shells stand among the best examples of structural engineering work of the 20th century. At a time when computers did not exist, Torroja's imagination and creativity were not constrained by the limits of the analytical methods available for structural design, and he was able to design and build economically innovative structures of the highest aesthetic quality. One of his major creations was the roof of the Frontón Recoletos, a unique two lobe thin shell that was destroyed during the Spanish Civil War. This paper reviews briefly the history of the Frontón, shows the results of a structural analysis of its roof by several Finite Element (FE) models of different complexity and precision, and compares FE results to those obtained by Torroja. FE results confirm the validity of Torroja's conceptual design, although he seems to have underestimated the internal forces and stresses in the roof. In addition, the paper analyses in detail the influence on the behaviour of the roof from its support conditions and from the stiffening ribs that Torroja designed but that never were built. As a result, the paper enables a better understanding of one of the masterpieces of Structural Art, and of simplified and complex shell analysis models, which is useful for the education of engineers as well as for future designs

Introduction

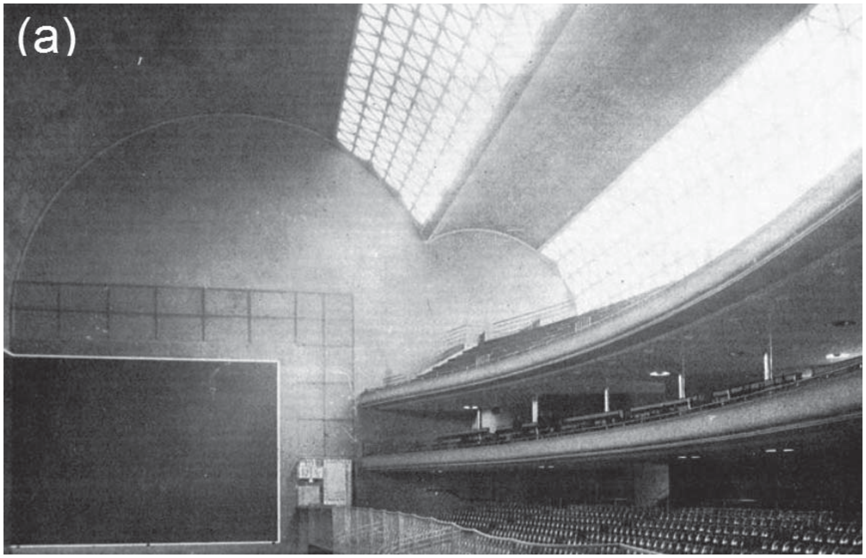
Shell structures figure among the most exciting man-built structures. Their attractiveness comes from the expressiveness, efficiency and good structural behaviour they have when properly designed as shown by the works of Candela,[1] Isler,[2] Nervi,[3] or Torroja[4] in concrete and Dieste[5] in brickwork. In these cases, shells are also very sustainable structures, as they employ small quantities of construction materials, require low maintenance, and have no durability problems.[6] However, thin shells are nowadays rarely considered as competitive alternatives for new designs as pointed out by Meyer and Sheer.[7] According to these authors, the difficulty to properly analyse and design this kind of structure is one of the causes of their loss of popularity. Some books provide a detailed explanation of shell design[8] and very interesting research is being done in shell optimization and form finding[9] but analysing the work of the shell master builders is one of the most attractive and inspiring ways to learn about shell design and construction. This idea guided previous works that provided new insights into the roofs built by Candela,[10] Tedesko,[11] and Dieste.[12] This paper aims to increase the understanding of thin concrete shell construction through the study of one of its masterpieces: the roof designed by Torroja for the Frontón Recoletos in Madrid, Spain.

Eduardo Torroja (1899-1961) is one of the most important structural engineers of the 20th century.[13] For almost forty years, he conducted intense activity as university professor, researcher, and consultant engineer.[14] He was especially outstanding in the design and construction of thin shell concrete structures, a technical field where his designs provoked enthusiasm due to their audacity, efficiency, and aesthetics.[15] The Algeciras Market Hall (1934), the Zarzuela Hippodrome Roof (1935), and the Frontón Recoletos (1935) are his three major concrete shell projects. To build such remarkable structures, Torroja developed new analysis methods, built scale models, and monitored scale models and real structures to check their safety, learn about their structural behaviour, and improve later designs.

Torroja explained his main works and structural philosophy in his two major books.[16] He also explained the details of the analysis and construction of Recoletos' roof in a report written on the occasion of his appointment as a member of the Real Academia de Ciencias Exactas, Físicas y Naturales (Royal Academy of the Exact, Physical and Natural Sciences).[17] Later works[18] have briefly explained the architecture and, qualitatively, the structural behaviour of Recoletos' roof, but none of them has analysed it exhaustively. This paper bridges this gap and explains the main lessons that can be learned from its design. To reach this goal, the roof is analysed with different FE models of increasing complexity and precision and the results of these analyses are compared to those published by Torroja.[19] Additionally, the influence of

Figure 1

Frontón Recoletos: (a) interior view and (b) exterior view [courtesy of Archivo Torroja – CEHOPU].

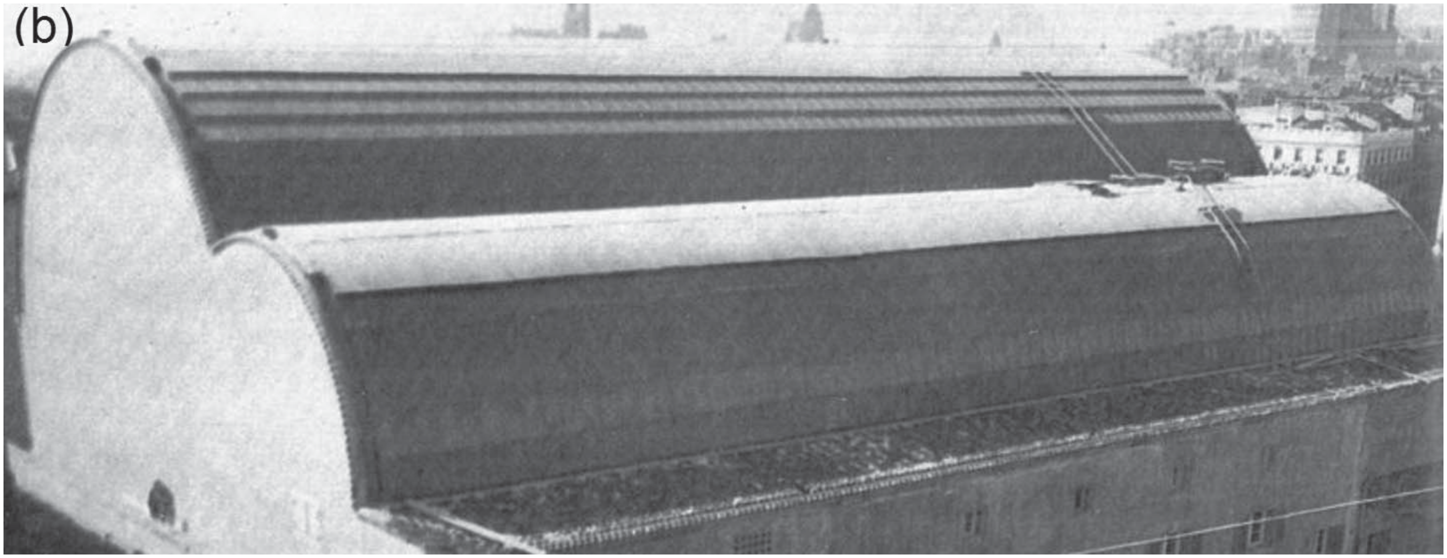


some design decisions not discussed by Torroja is analysed in detail. In doing so, this work enables a better understanding of (a) one of the key works in the history of reinforced concrete construction, (b) the accuracy of different models that can be used in shell design, and (c) global shell behaviour, which is useful for future designs and the education of engineers. The paper starts with a description of the Frontón Recoletos' roof and its engineering historical context. Then, the methods used by Torroja to design the roof and the main features of the FE analyses carried out by the authors are explained in detail and their results are compared. Next, the paper analyses the influence in the structural behaviour of the roof of its support conditions and of the different patterns of external stiffening ribs that Torroja designed but that were not built. Finally, the main conclusions of the work are drawn.

The Frontón Recoletos

The Frontón Recoletos (see Fig. 1) was a sports facility in Madrid designed by the architect Secundido Zuazo and the engineer Eduardo Torroja for playing a game called Basque Pelota. This game is played by two teams on a large rectangular playing pitch enclosed by front, side, rear walls in a building or place called frontón in Spanish. The two teams participate in a match whose aim is to prevent the opponents from launching a ball correctly against the front wall.[20] The roof of a frontón is one of its most difficult structural elements to design because it must cover a large area with no interior support, allowing at the same time the entry of natural light, and leaving a certain clearance between the playing pitch and the roof. To fulfil all these functional requirements, the roof of the Frontón Recoletos was designed as a thin concrete shell structure. The roof covered a surface of 55 x 32.5 m and, in those areas where skylights were needed, the shell was replaced by a triangulated structure designed for the insertion of glass panes. This design was the result of architectural, economic, aesthetic and construction schedule constraints and was considered by Torroja to be much better than two other proposals based on transverse or longitudinal truss girders.[21] Fig. 2 shows a cross section and a plan view of the building.

The shell had an innovative and attractive shape defined by two joined cylindrical sectors or lobes of horizontal and parallel axes (Fig. 3). The shell directrix was defined by two circular arches of radii 12.2 m and 6.4 m which sprang from the outer supports (points A and B in Fig. 3) with a vertical tangent and joined orthogonally along a common line parallel to the their axes (point C in Fig. 3) defining the outline of a seagull. The thickness of the shell was only 8 cm except at the connection between the cylindrical sectors where it increased to 0.3 m to resist the transverse bending moments and to adequately cover the reinforcement bars found there. Two 55 m long skylights covering almost the whole length of the Frontón were built. The first one was located in the largest cylindrical sector near the intersection between both lobes. The second one was placed in the smallest cylindrical sector near its connection with the outer wall. Reinforced concrete elements



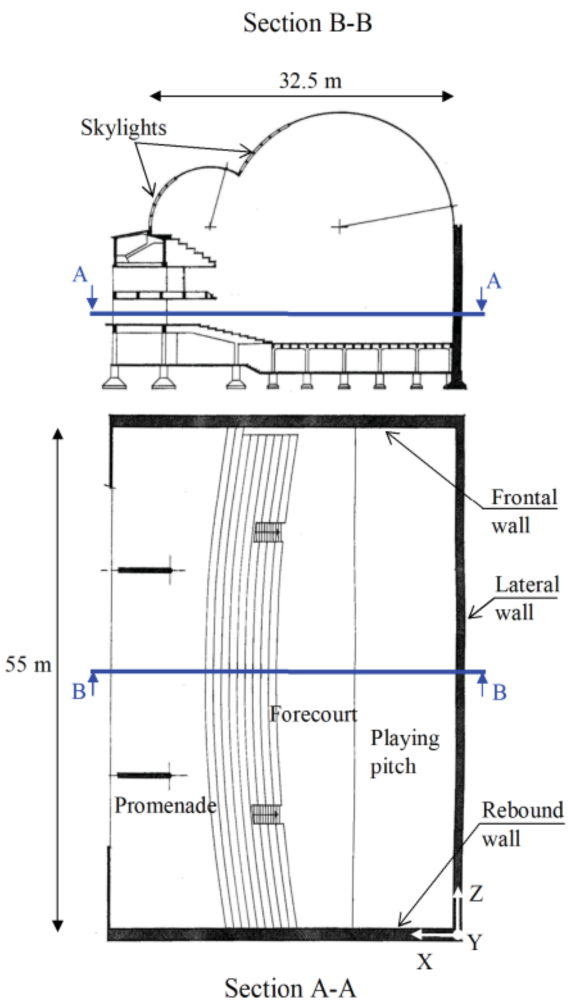
of the triangulated structure of the skylights had a depth of 0.3 m, a width of 0.17 m and a length of 1.4 m. The roof structure was supported at its two extreme longitudinal edges (lines represented by points A and B in Fig. 3) and at its two extreme directrices (sections with Z coordinate equal to 0 and 55 in Fig. 2) by means of different kinds of structures described in Antuña.[22] These structures allowed for the free longitudinal dilatation of the shell (along its "Z" axis in Fig. 2) whereas they restrained the transverse displacements (along axis "X" and "Y") at the shell springings. Additionally, structures supporting the two extreme directrices acted as a rigid diaphragm, and avoided any change of the shape and any vertical displacement of these directrices.

The structure of the whole building was completed in just 90 working days.[23] During the spring of 1937, and due to the Spanish Civil War (1936-1939), the roof was subjected to both direct hits and severe vibrations from aerial bombing. Such action was not considered in the structural design of the roof and caused severe deformation as well as the removing of several square meters of shell. Soon after the end of the war, Torroja made a proposal to repair the structure. This proposal was based on adding external reinforcement ribs to the roof and aimed to increase the overall rigidity of the structure as well as to recover the initial geometry through a prestressing of the ribs by means of turnbuckles. However, these repairs could not be finished because the roof collapsed on the night of the 15th August 1939. A new roof project with conventional transverse trussed girders every 5.5 m was drawn up in September 1939 and later built. The whole building of the Frontón Recoletos was demolished in 1973 and subsequently replaced by a residential building.[24]

Several features made the original Recoletos' roof an outstanding structure, especially among barrel vault concrete shells. First of all, Recoletos' roof was larger and more slender than previous barrel vaults designed by the German engineers (Dischinger and Finsterwalder) who pioneered the design and construction of this kind of constructions (see Table 1). Secondly, never before had an asymmetrical two-lobed thin concrete vault of such dimensions been built. Thirdly, the continuous shell was replaced by a triangulated structure in highly stressed portions of the barrel

Figure 2

Cross section (top) and plan view (bottom) of the Frontón Recoletos building [Torroja 1958].



vault to create the skylights, constituting a major innovation. Finally, Torroja's search for structural honesty, aesthetics, and ease of construction led him to design the roof without edge beams at the intersection between the lobes of the shell and without visible ribs.[25] These edge beams were common in previous designs such as the market halls of Frankfurt (1926-27) and Budapest (1930), but their use at Recoletos would have affected the perception of the structural behaviour and lightness of the structure. All of the above-mentioned characteristics of the roof made it an icon, but also made its structural design very difficult. Consequently, the building developer asked two eminent Spanish engineers, Eugenio Ribera and J.M. Aguirre, to supervise the design and write a report. The concluding remark of this report was:

> "(…) we think that the construction of the Frontón Recoletos is not only feasible, but also that it will be a new success of our architectural technique. It is specially praiseworthy the decision of the designers of covering this space with such a vaulted roof that, being the biggest of its kind in the world, will put Spain in a pre-eminent place in the list of technical advances. It is also praiseworthy the attitude of the designers who worked hard to explore new solutions and directions that reflect a progressive advance instead of following very well known paths, much easier and implying less responsibility"[26]

The next section describes how Torroja faced and overcame the design challenge as well as the results he obtained.

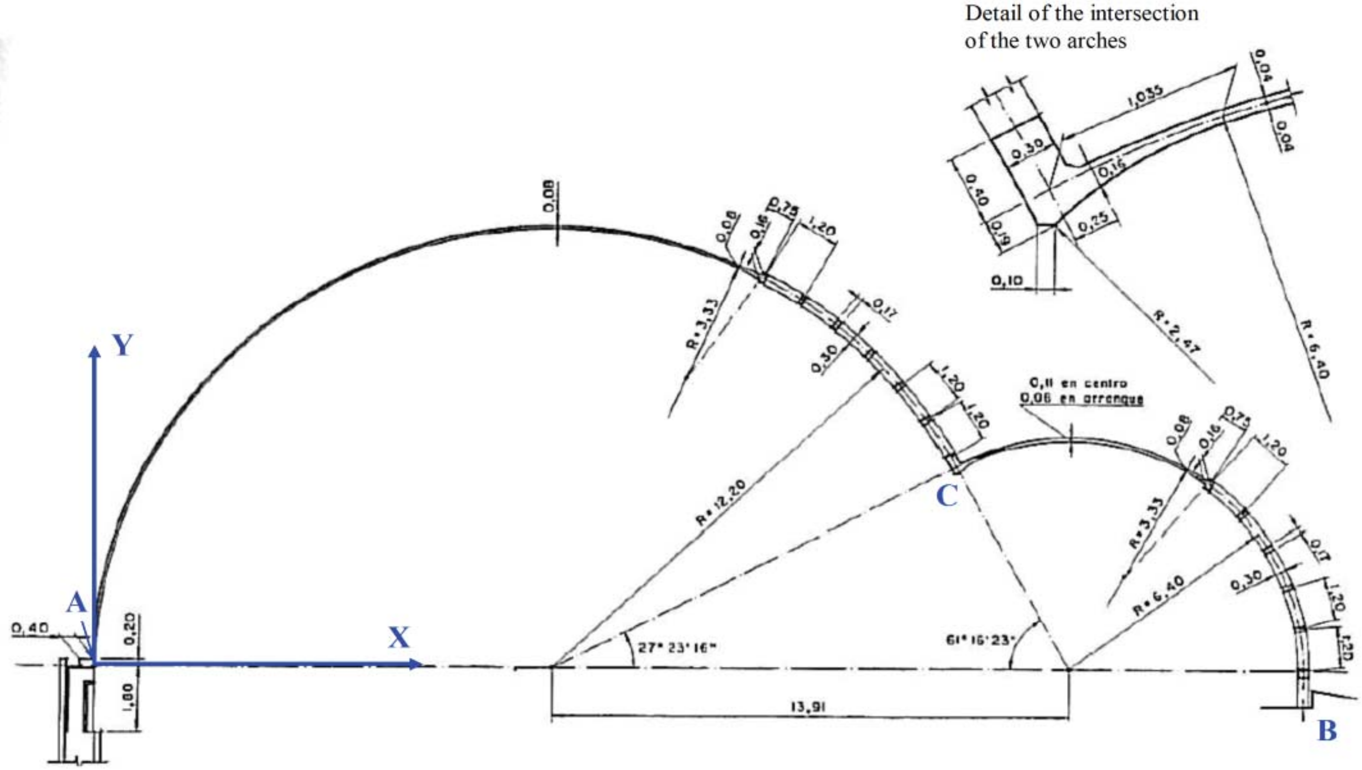
Analysis of the Roof Carried Out by Torroja

Shell structures were defined by F. Dischinger, as "structures formed by singly or doubled curved surfaces, the thickness of which is slight in comparison with the superficial area."[27] This definition was later completed by other authors[28] who considered that, furthermore, the structure had to be made of a material resistant to compression and tension, the goal of this other condition being to distinguish shells from other structures such as medieval vaults which only can resist compressive stresses.

In a general way, two types of internal forces can appear in a shell: membrane forces and bending forces (see Fig. 4). The importance of each one of these types depends on the thickness and shape of

Figure 3

Geometric definition of the directrix of the shell roof of the Frontón Recoletos [courtesy of Archivo Torroja – CEHOPU].



the shell, its support conditions, and its loading. The smaller the bending behaviour of the shell is, the better its structural efficiency, and the thinner it can be. Until the availability of computer use for structural design, the theoretical calculation of the shell internal forces and displacements was a complex task which was only possible for some shapes.[29] Therefore, shell design, especially in its infancy, combined theoretical and experimental knowledge and required abilities to innovate and deal with code gaps and possible distrust from project supervisors.[30]

Torroja based the analysis of Recoletos' roof on the methodologies developed by Dischinger and Finsterwalder for the design of the roofs of the market halls of Frankfurt and Budapest.[31] However direct application of the methods used in the design of those structures was not possible because (a) Recoletos' directrix was asymmetrical and had no edge beam at the intersection between the two arches of the directrix, and (b) Recoletos' larger size and higher rise made it necessary to consider wind loads. In addition, there was no theoretical design methodology able to take into account the real characteristics of the skylights and the variation of the cross section thickness at the intersection of the lobes.

Within this historical and technical context, Torroja analysed Recoletos' shell by considering it as a homogenous structure with

Table 5

Comparison of the barrel roofs of the Frankfurt market mall, Budapest market mall and Frontón Recoletos.

Name of the construction	Year	Type	Width w (m)	Length L (m)	Rise d (m)	Thickness h (m)	w/h	L/h
Frankfurt's Market Hall	1926-27	Circular barrel	14	37	4	0.07	200/1	530/1
Budapest's Market Hall	1930	Shallow circular barrel	12	40	1.9	0.06	200/1	665/1
Frontón Recoletos	1935	Intersected circular barrels	32.5	55	12.2 – 6.4	0.08	400/1	680/1

uniform depth and elasticity modulus. He justifiably neglected longitudinal bending moments (M_z in Fig. 4), longitudinal shear forces (Q_z in Fig. 4) and torsional moments ($M_{z\theta}$ and $M_{\theta z}$ in Fig. 4), and proceeded to solve the structural problem in two steps. First of all, the loading was considered to be resisted entirely by membrane forces. The resulting forces and displacements at the shell boundaries were not compatible with the known boundary conditions, and, in a second step, forces and displacements were applied to the shell boundaries in the amounts required to eliminate the incompatibilities resulting from the membrane forces. This second step introduced bending moments and shear forces in the shell, and the final forces and stresses were the sum of those obtained at each of the two steps. The calculations carried out by Torroja were based on a system of fifty-four differential equations obtained from the equilibrium and compatibility conditions of the shell's structure. Its solution provided the membrane stresses and bending forces in the shell as well as its deflections. Afterwards, Mohr's circles corresponding to the membrane stresses were drawn and used for obtaining the principal stresses, the stress trajectories and the isobars (Fig. 5a and 5b) along the middle surface of the shell. The most unfavourable section was the central directrix (section B-B in Fig. 2) where the maximum obtained deflections were around 15 cm at the connection between both lobes[32] and the structure internal stresses and forces varied between 0 and 5.7 MPa for compressive stresses, 0.6 and 7.8 MPa for tensile stresses, -10 KN m/m and 10 KN m/m for transverse bending moments and -3.4 KN/m and 2.5 KN/m for transverse shear.[33] With all these results, the shell reinforcement was calculated and detailed.

The solution of the mathematical problem took several months[34] and was attempted by two different teams. The results obtained by these teams did not perfectly match[35] and the theoretical work was supplemented with an experimental investigation on a reduced scale model (Fig. 6) with a scale factor of 1/10. Strains and deflections of the built shell were measured at the removal of the formwork and during the early stages of the roof life and were in a general good agreement with the expected values.[36] The analysis of the roof, its scale model, its construction, and even a discussion on the causes of its collapse were explained by Torroja.[37]

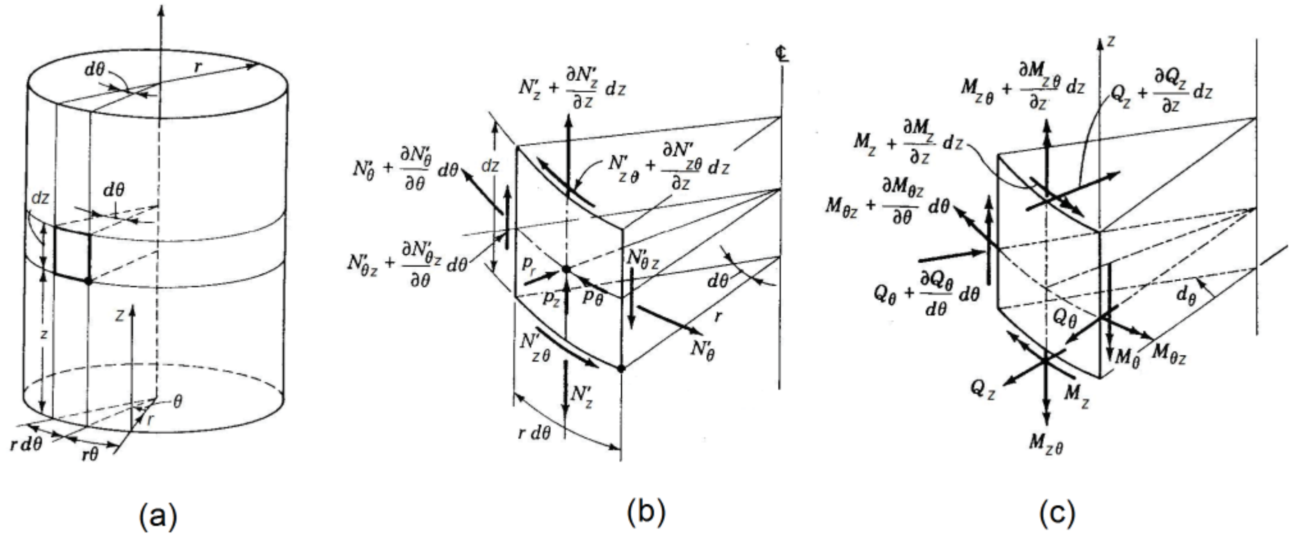
Analysis of the Roof by the Finite Element Method

Introduction

This paper aims to delve into the behaviour of concrete shells through the analysis of one of the masterpieces of that form of construction. To reach this goal, this section starts by analysing Recoletos' roof with four FE models of increasing complexity and precision and compares their results with those provided by Torroja. Then the influence of some parameters of the design (support conditions of the shell at its extreme directrices, use of external ribs for stiffening the shell) is discussed.

Figure 4

Cylindrical shells: (a) geometrical definitions, (b) forces from membrane theory, (c) forces from bending theory [adapted from Billington, *Thin Shell Concrete Structures*].



Analysis of the roof

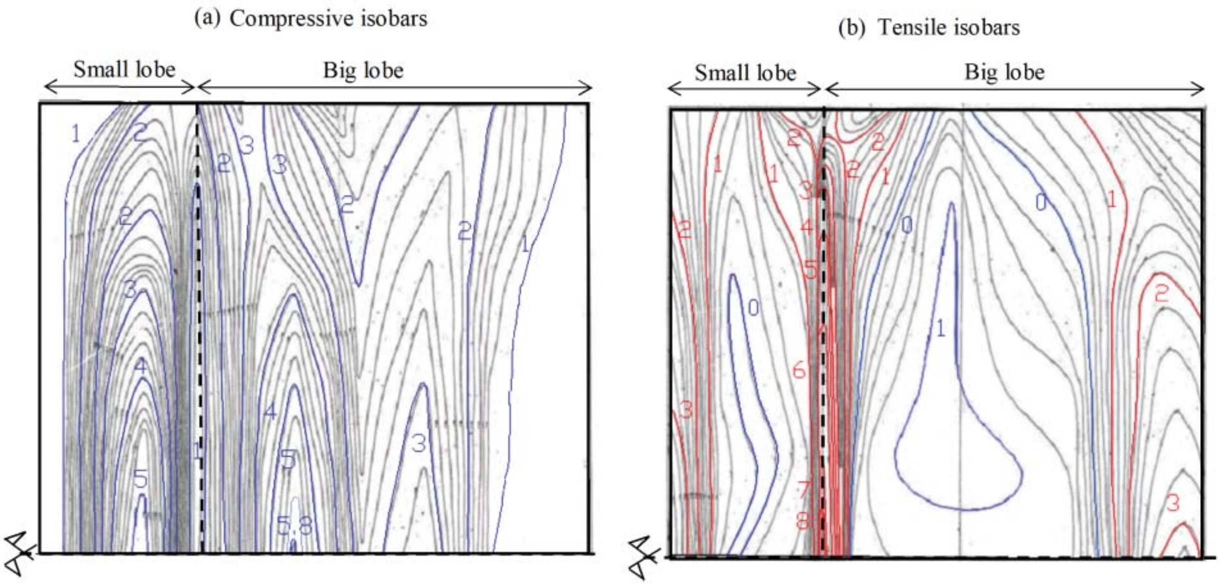
The finite element (FE) linear elastic structural analysis is based on the development of four successive models of the structure named FEM-1 to FEM-4 with the commercial software Lusas[38] whose main characteristics are listed in Table 2. Differences between the FE models relate to the following factors: shell thickness, modelling of the skylights, shell support conditions, and loads applied. FEM -1 corresponds to the analysis done by Torroja as described in Section 3, whereas FEM-4 is the closest approach to the built structure. Lusas' QSI4 thin shell element and BMS3 beam element have been used for modelling the shell and the bars of the skylights, respectively. The QSI4 is a 4-node element with four degrees of freedom per node. This element is commonly used in the analysis of three-dimensional thin shell structures, and considers both membrane and bending behaviour. The BMS3 element is a 3-node straight beam with six degrees of freedom at the beam end nodes. Its geometric properties are constant and it includes the effect of shear deformations.

Material properties and loads have been taken from Torroja's report.[39] Therefore, the analysis used a Elasticity Modulus (E) of 29400 MPa and a zero value of the Poisson coefficient (ν), except in FEM-4 where a more realistic value of ν equal to 0.2 was used. Table 3 lists both the loads used by Torroja and those applied in each of the FE models. These loads correspond to three elementary cases: dead load, snow, and wind.

Four types of results were used to compare Torroja's and the FE models: deflections of the central directrix, isobars of membrane compressive and tensile stresses, and transverse bending moments along the central directrix. Torroja published the isobars and internal force diagrams.[40] He also included a drawing[41] with a graphic scale comparing the deflections of one shell directrix for the theoretical and reduced scale models with the deflections measured in the built structure. However, when trying to analyse Torroja's deflection results a problem arose: he did not indicate the position of the directrix where the results had been obtained, neither the value of the deflections, nor the load combination used to obtain them. To solve this problem, the authors conducted

Figure 5

Isobars corresponding to the membrane compressive (a) and tensile stresses (b) on the middle surface of Recoletos' roof obtained analytically by Torroja. The middle surface of the shell is developed. Only half of the roof is drawn. Values in MPa. Blue lines represent compressive stresses and red lines represent tensile stresses [source: Torroja, "Comprobación y comportamiento"].



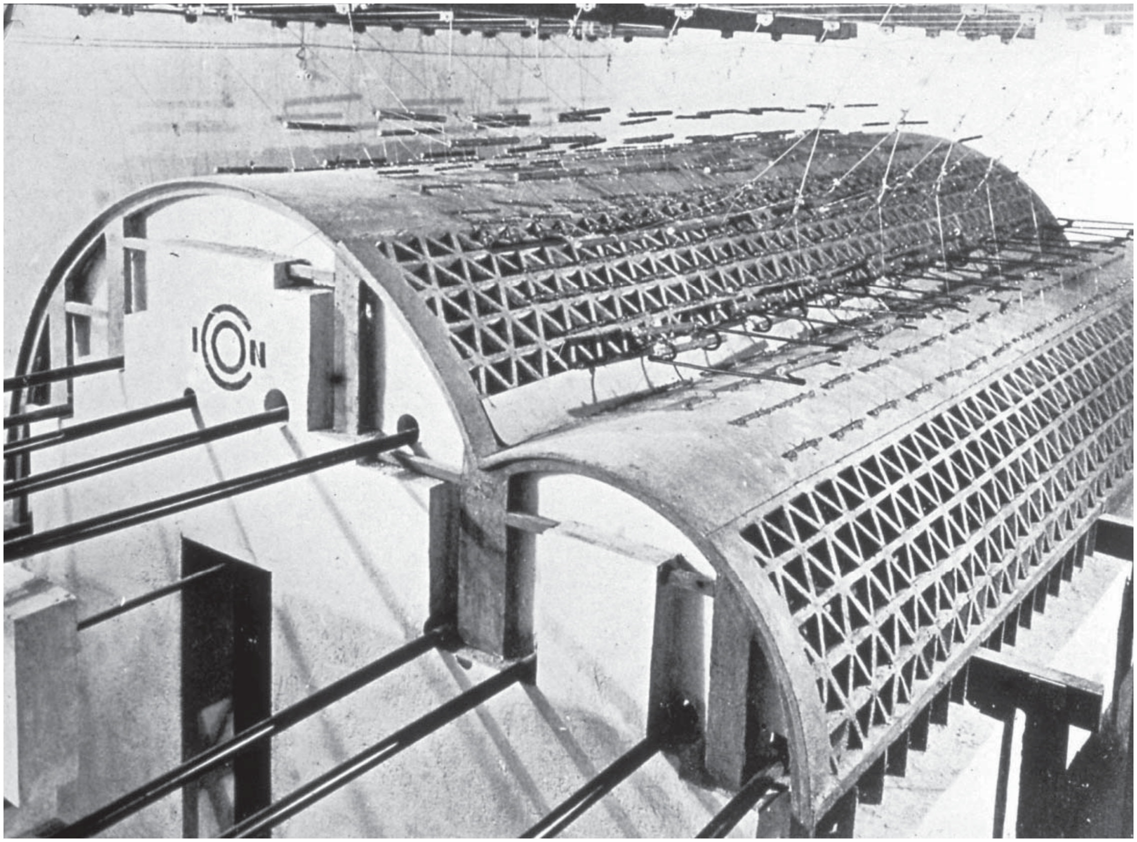
a parametric study which concluded that deflections published by Torroja corresponded to the central directrix and to the load case "dead load + snow + wind-1". It must be mentioned that Torroja's deflection results were graphically measured by the authors of this paper on the drawing published[42] and that an error in the measured values of +/- 1.5 cm was unavoidable due to misreading.

Fig. 12a shows the deformed shape of the central directrix according to each of the FE models as well as the deformations of the scale model and the built structure published by Torroja. Graphical comparison of the results shows a good agreement between FE and Torroja's results and validates the numerical models. In all cases, the area of the shell in the neighbourhood of the connection between the two lobes experienced the greatest deflections. FEM-1 and not FEM-4, provided the closest approach to Torroja's results, although FEM-4 is the model most similar to the real built structure. This difference might be explained by the influence on the results of the real values of factors such as the elastic modulus and the loads. To gain additional knowledge on the causes of this discrepancy, the authors studied two additional models: FEM-4* and FEM-4**. These models are the same as FEM-4 except for the value of E used in the structural analysis. FEM-4* used a value of E*=0.9E and FEM-4** used a value of E**=0.8E. Results of these new analyses are shown in Fig. 12b, whereas Table 4 lists the vertical displacement of the connection between the two lobes (point C in Fig. 3) for each one of the analysed cases. FEM-1 and FEM-4** provide results which perfectly fit the values of the built structure, if a tolerance of 1.5 cm for the values of the displacements published by Torroja is considered as previously explained.

The isobars of compressive and tensile stresses in the middle surface of the shell resulting from the models FEM-2 and FEM-4** are shown in Fig. 13a to Fig. 13d. Fig. 13 does not include results from FEM-1 because this model does not include the actual thickness of the shell at the junction of the two lobes and,

Figure 6

Reduced scale model of Frontón de Recoletos' roof [courtesy of Archivo Torroja – CEHOPU].



therefore, overestimates the stresses. To simplify comparison and understanding of these diagrams, the areas where the FE models' stresses exceed the maximum values obtained analytically by Torroja, are coloured in darker blue for compressive stresses (Fig. 13a and 13c) and in red for tensile stresses (Fig. 13b and 13d). The overall shape of the isobars is very similar to that published by Torroja (Fig. 5a and 5b) and confirms Torroja's general layout of the reinforcement.

On the other hand, Table 5 and Fig. 14, 15 and 16 detail the principal stresses and transverse bending moments along the central directrix for all the models. In the big lobe, maximum compressive stresses range from the value of 5 MPa obtained by Torroja to values of 7.2 MPa (FEM-3), 7.6 MPa (FEM-4), 7.8 (FEM-4**) and 7.9 MPa (FEM- 2). In the small lobe, Torroja obtained a maximum compressive stress of 5.8 MPa whereas the maximum compressive stresses obtained by FEM-2, FEM-3 and FEM-4** are of 4.8 MPa, 4.4 MPa, and 3.7 MPa respectively. It is worth noticing that maximum compressive stresses in the big lobe are obtained in the same location in all the cases, but this situation is not repeated in the small lobe, where the maximum compressive stresses are closer to the shell springings than supposed by Torroja in a

Table 6

Main features of the FE models of the Frontón Recoletos' roof.

FE model	Shell thickness	Skylights modelling	Supports	Number of Joints	Number of Shell Elements	Number of Beam Elements
FEM-1 (Fig. 7)	Constant and equal to 8 cm	Shell of 8 cm of thickness	Supports restraining only displacements in the directions of the axes X and Y. Additionally, supports of the central directrix also restrain movements in the Z direction (see Fig. 7)	3721	3600	0
FEM-2 (Fig. 8)	Variable (see Fig. 3)	Shell of 8 cm of thickness	idem FEM-1	4327	4200	0
FEM-3 (Fig. 9)	idem FEM-2	Beams of 0.17 m of width, 0.3 m of depth and of 1.4 m length	idem FEM-1	44211	30230	38255
FEM-4 (Fig. 9 and 10)	idem FEM-2	idem FEM-3	Springs with the stiffness of the real supports	44211	30230	38255

Figure 7

3D view of the FE number 1 showing its FE mesh and support conditions.

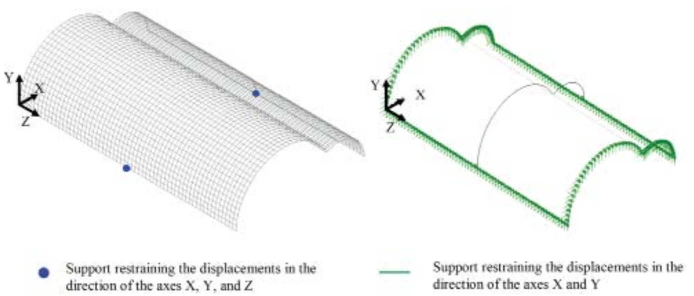


Figure 8

FE number 2: Cross section and detail showing the variation of the thickness of the shell in the neighbourhood of the intersection between the two lobes. 3D view is the same as for FE model 1.

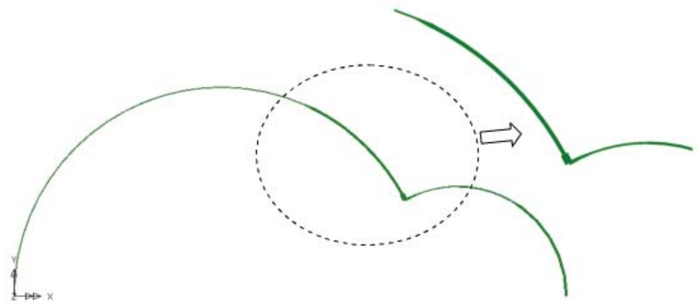


Table 7

Loads used by Torroja from “Comprobación y comportamiento” and loads used in the FE models. Surface loads acting on shell elements are given in KN/m^2 and linear loads acting on beams are given in KN/m.

Figure 9

FE number 3: 3D view. The reinforced concrete shell is coloured green whereas the reinforced concrete beams of the skylights are coloured purple.

Figure 10

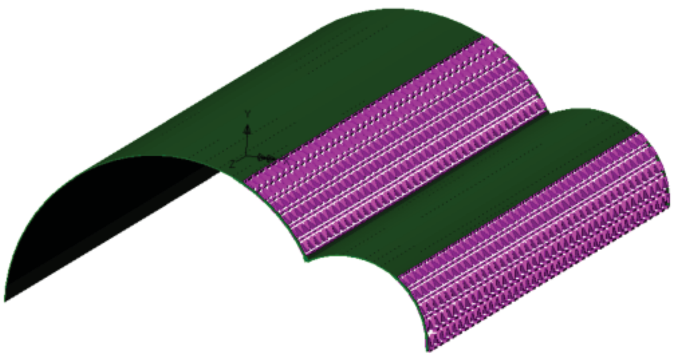
FE number 4: Plan view of the supports and detail showing the springs in the X and Z directions. 3D view is the same as for FE model 3.

Analysis	Dead load	Snow†	Wind†
Torroja	Constant‡ and equal to 2.45	Snow = 0.637cosφ	Two hypotheses: Wind without suction effects: Wind-1=0.981sinφ Wind with suction effects: Wind-2=0.392sinφ– 1.274cosφ
FEM-1	idem Torroja	idem Torroja	Wind-1, Wind-2
FEM-2	idem Torroja	idem Torroja	Wind-1
FEM-3	Shells: idem Torroja	Shells: idem Torroja	Wind-1
FEM-4	Beams:§ 0.98	Beams:§ 0.255 cosφ	

†See Fig. 11.

‡The dead load used by Torroja is an average value which includes the self-weight of :
(1) the concrete shell (with a thickness of 9 cm for taking into account possible construction errors),
(2) the glass panes of the skylights, and
(3) the insulation material used in the roof.

§Loads acting on the beams are obtained according to the tributary area of each beam.



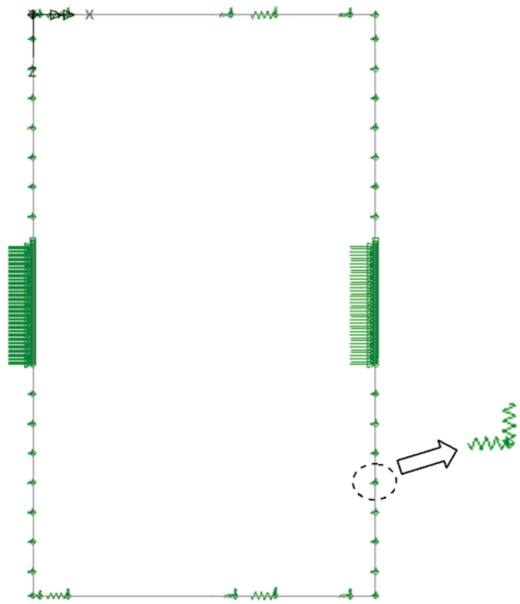
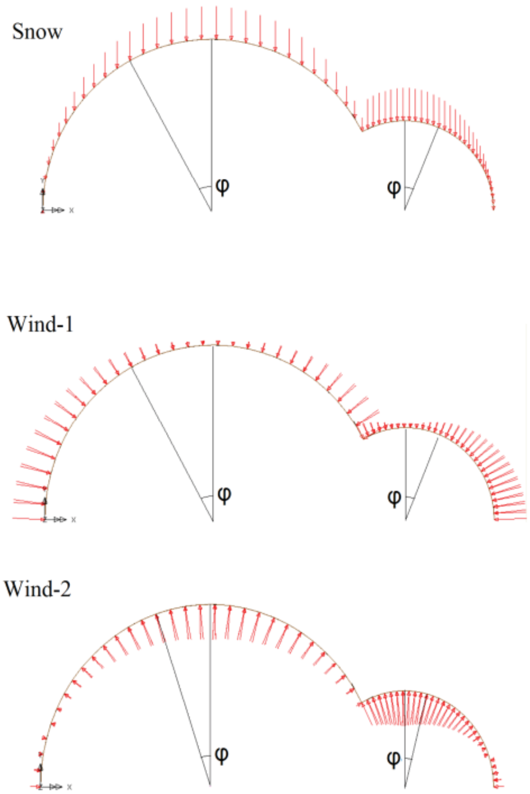


Figure 11

Snow and wind loads considered by Torroja.



magnitude between 1 m and 2.1 m depending on the FE model considered. On the other hand, both Torroja and the FE models conclude that principal stresses in tension only appear at the lobes intersection and are perpendicular to the shell directrix. Values of these stresses range from 8 MPa (Torroja) to 28.7 MPa (FEM-1), 18.7 MPa (FEM-2), 16.7 MPa (FEM-3, 4**) and 16.6 MPa (FEM-4). To resist these high tensile stresses Torroja designed a tension chord perpendicular to the shell directrix made of square steel bars embedded in the concrete of the shell. It must be said that the results of FEM-1 tensile stresses at the connection between the two lobes are not valid because of the difference existing in this

Figure 12

Deformed shape of the central directrix of the shell for different models. Deflections are multiplied by a factor of 200.

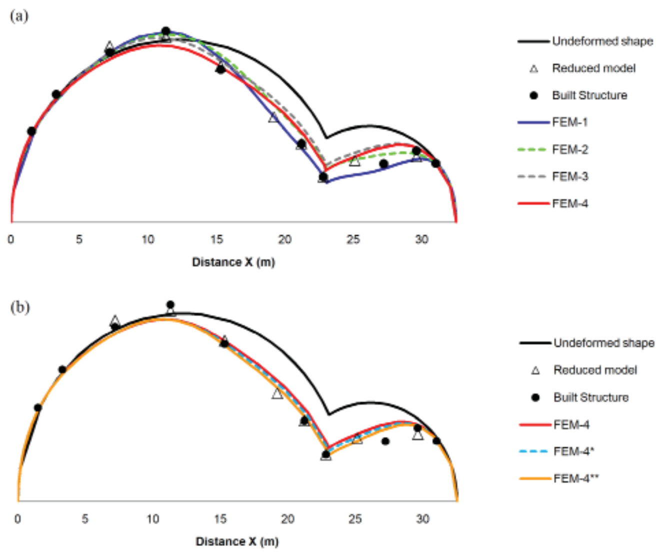


Table 8

Displacements of the connection between the two lobes of the shell.

Model	Absolute displacement (cm)	Absolute displacement - displacement of the built structure (cm)
Torroja Theoretical	-13	-1.3
Reduced Scale Model	-15	0.7
Built structure	-14.3	0
FEM-1	-14.9	0.6
FEM-2	-10.4	-3.9
FEM-3	-8.9	-5.4
FEM-4	-10.6	-4.3
FEM-4*	-11.7	-2.6
FEM-4**	-13.0	-1.3

Figure 13

Plan view of the Isobars corresponding to the membrane compressive and tensile stresses on the middle surface of Recoletos' roof: (a) and (b) FEM-2, (c) and (d) FEM-4** , (e) and (f) FEM-6, (g) and (h) FEM-7. Only half of the roof is drawn. Values in MPa. Negative values correspond to compressive stresses and positive values to tensile stresses.

area between the real thickness of the shell and the thickness of the shell considered in FEM-1.

Fig.16 shows the transverse bending moments according to Torroja and the FE models. Once again, the shapes of all the diagrams are very similar but the maximum bending moments (in absolute value) obtained by Torroja (10.3 and 6.2 KN m/m for the small and big lobes respectively) are smaller than those predicted by the FE models. These models give maximum absolute values of the bending moments between 15.8 KN m/m and 19.5 KN m/m for the small lobe, and between 13.0 and 22.1 KN m/m for the big lobe. These bending moments predicted by the FE models might be responsible for a longitudinal crack that appeared in the middle of the big lobe when the formwork of the shell was removed and which Torroja himself attributed to "a concentration of stresses due to bending moments."[43] On the other hand, longitudinal bending moments from the FE models are negligible as supposed by Torroja. Finally, it is important to notice that simple models such as FEM-1 and FEM-2 reveal insight into the global behaviour of the shell and are much easier to build than the models that include a perfect definition of the skylights (FEM-3 and FEM-4). Therefore, this work shows that simplified models can be very useful for the preliminary design of concrete shells with skylights or of roofs with complex three-dimensional behaviour such as the grid shells designed e.g. by Schlaich, Bergermann und Partner.[44]

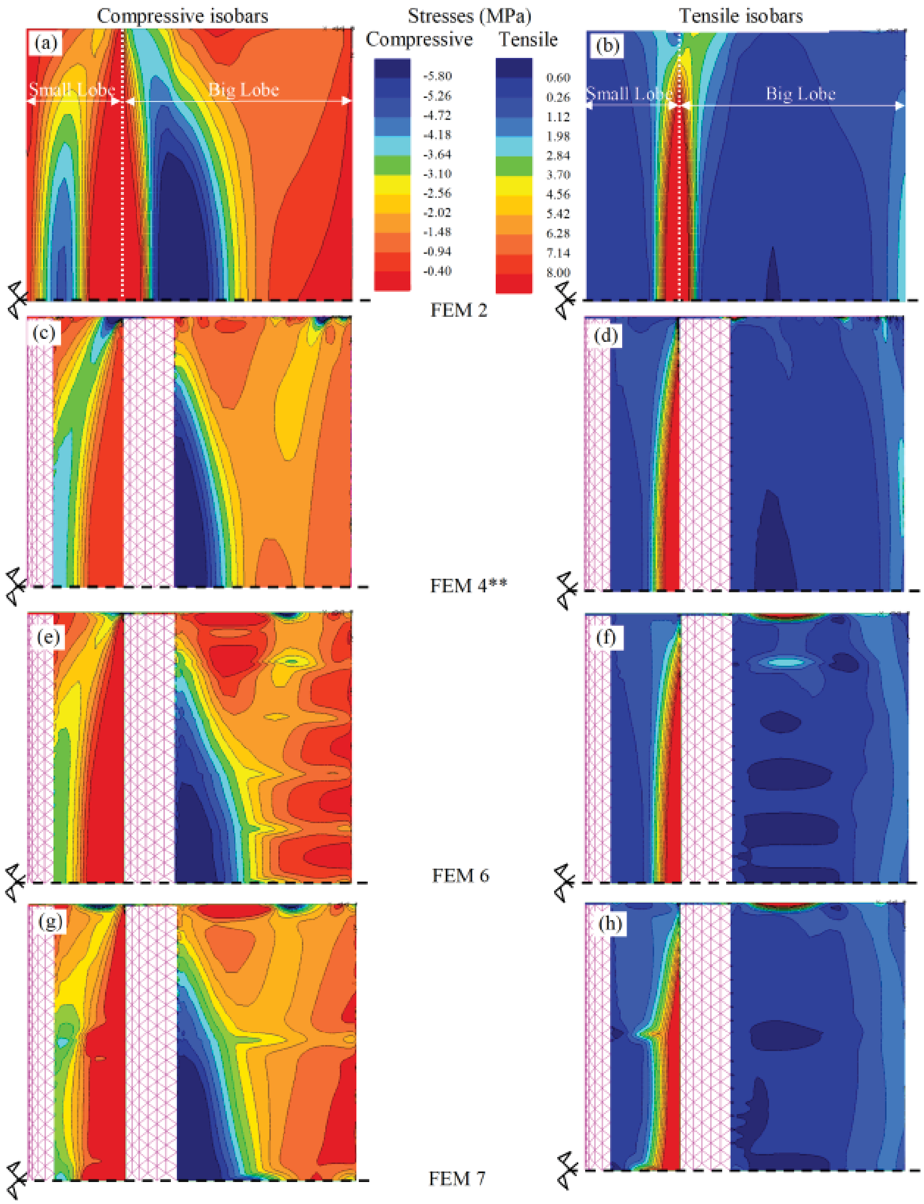


Table 9

Maximum principal stresses and transverse absolute bending moments in the central directrix. Stresses are given in MPa and bending moments in KN m/m. All the magnitudes are given as their absolute value.

Model	Big Lobe			Small Lobe		
	Compressive Stress	Tensile Stress	Bending Moment	Compressive Stress	Tensile Stress	Bending Moment
Torroja Theoretical	5.0	8.0	6.2	5.8	8.0	10.3
FEM-1	9.4	28.7	18.5	6.7	28.7	19.5
FEM-2	7.9	18.7	22.1	4.8	18.7	16.8
FEM-3	7.2	16.7	13.0	4.4	16.7	15.8
FEM-4	7.6	16.6	13.6	3.5	16.6	17.5
FEM-4*	7.8	16.8	14.1	3.7	16.8	18.6
FEM-4**	7.8	16.7	14.1	3.7	16.7	18.7
FEM-5	0	0	224.0	0	0	224.0
FEM-6	6.6	15.8	2.2	3.5	15.8	16.2
FEM-7	6.5	16.2	4.2	4.2	16.2	5.5

Influence of the Support Conditions of the Roof at its Extreme Directrixes on its Structural Behaviour

The extreme slenderness of Recoletos' roof was possible thanks to its three-dimensional behaviour derived from both the curvature of the roof and the support conditions at the extreme directrices. These supports acted as a rigid diaphragm that prevented any deformation of the structure in the XY plane. To check the importance of these supports, the authors carried out a new FEM analysis (FEM-5). FEM-5 is very similar to FEM-2, the only difference between them being that in FEM-5 the supports responsible for the rigid diaphragm action were removed, and therefore, the extreme directrices were free to deform.

Fig. 17 shows the transverse bending moments in FEM-5. Examination of this Figure reveals that: a) three-dimensional behaviour of the structure is no longer present as all the directrices of the shell have exactly the same bending moments independently of their Z coordinate, b) transverse bending moments have been multiplied by a factor between 5.6 and 18 when compared to FEM-2 results and now range from a minimum value of -224.0 KN m/m to a maximum value of 123.2 KN m/m. The high values of the bending moments indicate that bending behaviour is now much more important than membrane behaviour and a considerable increase of the depth of the concrete section and of the steel reinforcement of the roof would be required to sustain the loads. Therefore the decision to build the rigid diaphragms was crucial for the correct structural behaviour of the roof. Without these diaphragms, the roof works as a pair of barrel vaults with a two-dimensional behaviour (in fact, as a pair of arches) from which the central support has been removed. This was the common interpretation of the structural behaviour of the roof among the layman, an interpretation that, fortunately, was far from reality.[45]

Influence of Placing Stiffening Ribs in the Exterior Part of the Shell

As explained in Section 2, deformation due to the bombing suffered by the roof during the Spanish Civil War caused its collapse just when the construction of some external stiffening ribs was

Figure 14

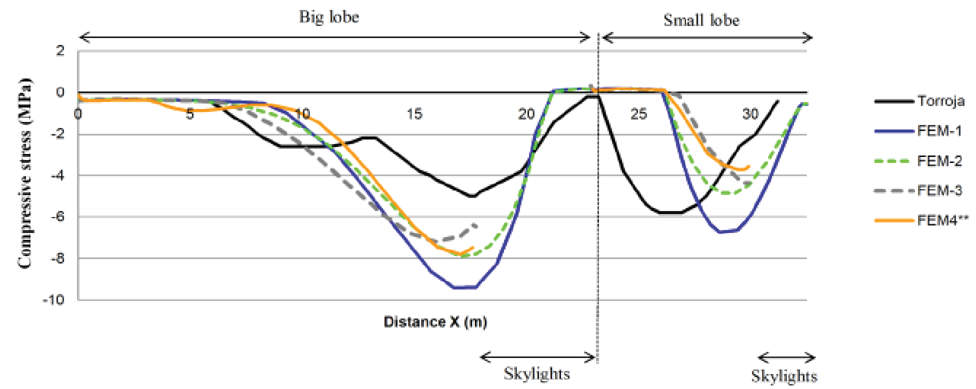
Principal compressive stresses at points along the central undeveloped directrix for different types of analysis. FEM-4 results are very similar to those of FEM-4**.

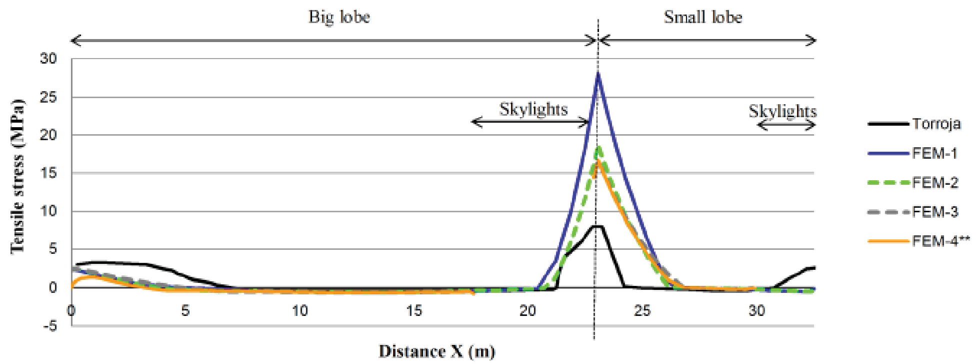
Figure 15

Principal tensile stresses at points along the central undeveloped directrix for different types of analysis. FEM-4 results are very similar to those of FEM-4**.

Figure 16

Transverse bending moments along the central undeveloped directrix for different types of analysis. FEM-4 results are very similar to those of FEM-4**. Positive bending moments produce tension in the top face of the shell.





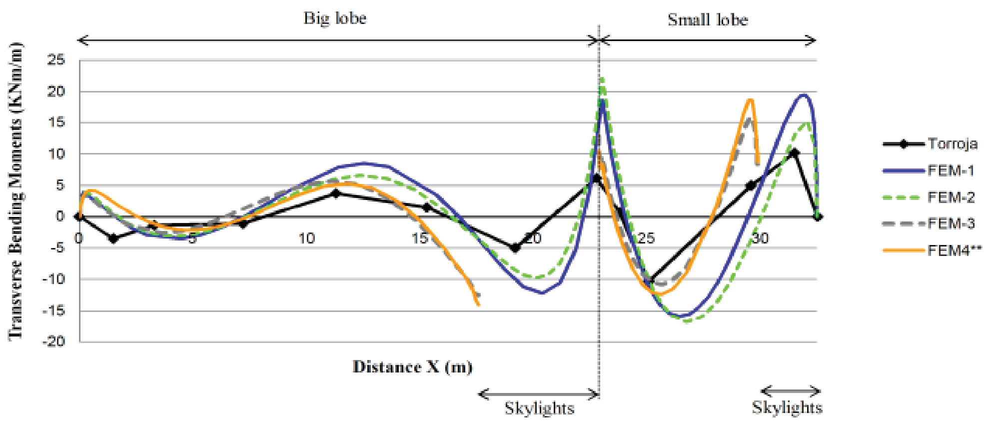


Figure 17

Transverse bending moments in FEM-5. Values in N*m/m.

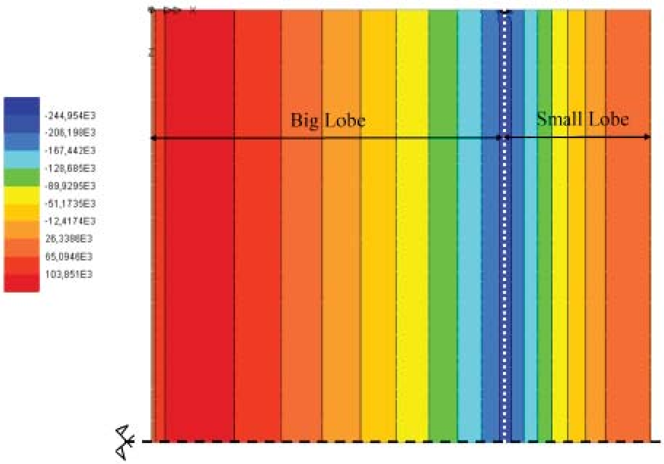
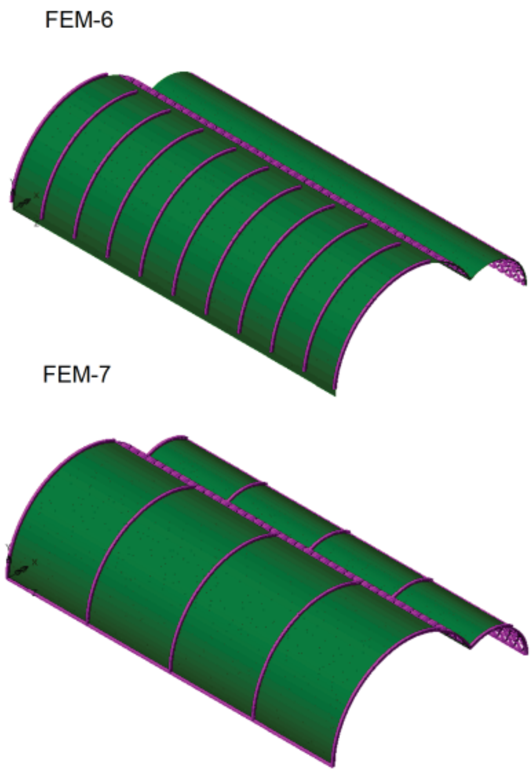


Figure 18

3D view of FE models 6 (top) and 7 (bottom).



about to begin. Those ribs were very important because they were intended to restore the structural capacity of the roof, but no structural analysis related to their design has been found by the authors, either in the documents kept by the Torroja Archive.[46] Furthermore, some disagreement surrounds the ribs as different designs have been explained by Antuña[47] and Torroja[48] on one side, and Torroja[49] on the other side. According to Antuña, the strengthening of the roof consisted in external ribs covering only the big lobe and placed every 5 m. This opinion is supported by a drawing where a section of the shell including the rib is shown but the spacing between two consecutive ribs is not indicated.[50] On the other hand, a drawing of the repair proposal published by Torroja shows the whole roof repaired with stiffening ribs placed every 13.75 m and covering both the big and the small lobes.[51]

Within this general context, this section aims to study the efficiency of the two alternative published designs. To reach this goal, two new FE models, namely FEM-6 and FEM-7, based on FEM-4 were built. These models included stiffening ribs as proposed by Antuña[52] and Torroja[53] respectively. In both cases the ribs were modelled as an overhanging beam with a depth of 0.45 m and a width of 0.3 m according to the construction drawings.[54] Fig.18 shows a 3D view of the two new models.

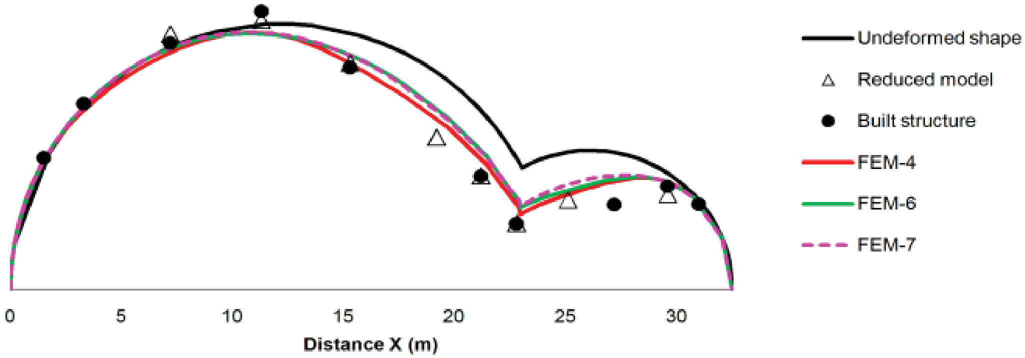
Fig. 19 shows the deformed shape of the central directrix of the shell with and without stiffening ribs. Maximum displacements occur at the intersection between the two lobes and have a maximum value of 9.1 cm (FEM-6) and 9.3 cm (FEM-7). These displacements are 12% and 14% lower than those of FEM-4 at the same point. Deflections in the small lobe are higher in FEM-6 than in FEM-7, as FEM-6 does not have any rib in the small lobe. The ribs also reduce considerably the transverse bending moments along the central directrix in the places where they exist

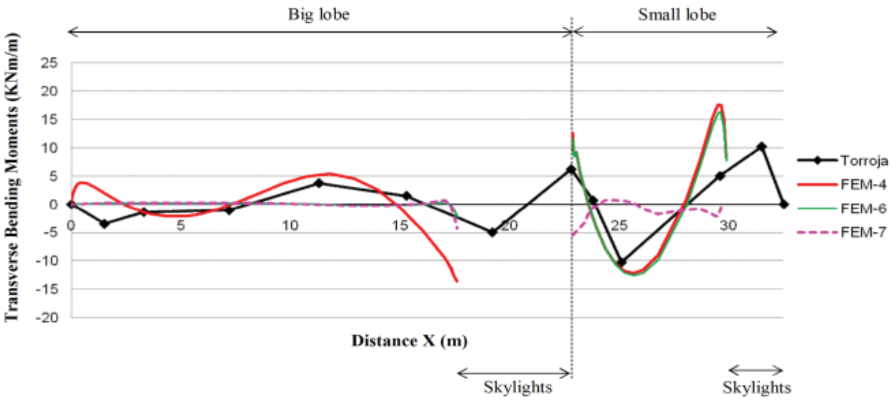
Figure 19

Deformed shape of the central directrix of the shell for different models. Deflections are multiplied by a factor of 200.

Figure 20

Transverse bending moments in different models. Positive bending moments produce tension in the top face of the shell.





as shown by Fig. 20 and Table 5. For example, the minimum bending moments in the big lobe in FEM-6 and FEM-7 are -2.2 and -4.2 KN m/m. These values represent only 16% and 31% respectively of the most unfavourable bending moment given by FEM-4 at the same location. Figs. 13e to 13h show the isobars of compressive and tensile stresses on the middle surface of the shell, whereas Table 5 contains the maximum values of these stresses in the central directrix. Comparison of these results with Fig. 13c shows that the construction of the ribs does not produce significant changes in the stress distribution, even though compressive stresses are smaller in FEM-6 and FEM-7 as the area in darker blue is smaller in Fig. 13e and 13g than in Fig. 13c. It can also be seen that a small concentration of compressive stresses appears in areas where the shell joins the ribs.

In conclusion, both rib patterns have a substantial positive effect in the global structural behaviour of the shell as they reduce both displacements and transverse bending moments. The solution defined by FEM-7 seems especially interesting because it reduces bending moments in both lobes and these bending moments were the cause of some cracks in the built structure as explained at the end of the section "Analysis of the roof." Furthermore, this solution employs less material and formwork making it more economical and easier to build.

Conclusions and Future Work

This paper analyses the structural behaviour of the roof of the Frontón Recoletos, an elegant and innovative structure designed by the Spanish engineer Eduardo Torroja in 1935. The FE modelling of the roof validates the conceptual design done by Torroja although the internal forces and stresses in the shell given by the FE models are larger than those predicted by him. In addition, the paper enables a better general understanding of the structural design of thin concrete shells, and of the important role that some elements such as diaphragms and stiffening rings play in their behaviour. At the same time, this study highlights how FE models with shell elements can be useful tools for the design of complex three-dimensional trussed structures and points out areas where additional research on Recoletos' roof is needed. More specifically, this future research should focus on the nonlinear and time-dependent behaviour of the roof (consideration of buckling, creep and shrinkage) and on its shape optimization.

Recoletos' roof stands as a great example of structural design and collaboration between the architect and the engineer compared to the present when some landmark buildings and bridges are designed following mainly aesthetic reasons and without too much consideration given to structural requirements.[55] The roof was the result of a careful study of alternatives that considered both aesthetics and costs; it was built on schedule and was aesthetically superb. In addition, sustainability was considered in the design by (a) using small quantities of construction materials and a reusable formwork and (b) designing skylights that enabled a reduced consumption of electricity for lighting. All these characteristics make Recoletos a masterpiece of Structural Art, a practical application of Torroja's ideals of structural honesty and simplicity, and an inspiring work for future designs.

But the story of Recoletos is also the story of an extraordinary human being, Eduardo Torroja. A person of incredible courage and talent, who was able to design, calculate by hand, and construct a unique roof that surpassed contemporary designs, using his structural knowledge and intuition. Recoletos also speaks about Torroja's innovative and curious character that led him to create the first structural monitoring company in Spain and to place measuring devices in the roof to learn from its actual behaviour. Furthermore, Recoletos is also an example of Torroja's altruism and generosity as he considered the roof a way to develop science, and wrote many publications to share the knowledge he gained from this work with the scientific-technical community. This kind of writing is of special value today because it enables the engineers of the present to learn from the masterpieces of the past and because it also encourages present-day designers to write about their technical work and aesthetic motivation for the present and future generations to benefit from. But above all, Recoletos shows us the humility of a genius who was able to reflect on his design and, recognizing that the existence of the reinforcement ribs could have avoided the collapse of the roof, wrote "had I to build it again (Recoletos' roof), I should provide reinforcement ribs."[56] All these features make Torroja an outstanding example to engineers and architects of all ages.

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ANALYSIS OF THE DESIGN CONCEPT FOR THE IGLESIA DE LA VIRGEN DE LA MEDALLA MILAGROSA

Ashley P. Thrall and Maria E. Moreyra Garlock

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Abstract

The Iglesia de la Virgen de la Medalla Milagrosa, or Miraculous Medal Church, exemplifies Félix Candela's mastery of discipline and play with the hyperbolic paraboloid (hypar) form. Candela designed and built this thin shell concrete structure in Narvarte, Mexico City between 1953 and 1955. His design concept was developed from his asymmetrical "umbrella" hypar form which he then tilted and warped to form half of each bay of the nave of Milagrosa. This paper first presents finite element analyses and a discussion of the structural form for each stage in the development of this design concept. Then an analysis of two adjacent bays is presented assuming a uniform thickness of 4cm (1.6in). In the actual structure, Candela adds a scalloping pattern which thickens the top ridge to 14 cm (5.5in). Through additional analysis with this added weight, this paper finds that significant tensile forces would develop without the scalloping ridge. The scalloped ridge therefore serves both structural and aesthetic functions.

Introduction

Félix Candela's Iglesia de la Virgen de la Medalla Milgrosa, or Miraculous Medal Church (hereafter Milagrosa), represents a reinterpretation of the Gothic style using the hyperbolic paraboloid (hypar) form (Figure 1). He designed and built the structure between 1953 and 1955 in Narvarte, Mexico City for a church committee that favored a traditional, Gothic cathedral. However, Candela focused on one key concept of Gothic: using minimal material to span a large space. The doubly-curved hypar surface was an ideal structural form to achieve this objective. It was not until construction had already begun that that committee realized that Candela had not used the traditional interpretation of the Gothic.[1]

Candela remarked that "in reality, the idea for the church came from a French engineering text, where I had seen a structure like this, with peaks and four paraboloids but forming four faces, very pointed, and that gave me the idea that with the paraboloids I could make these forms of an 'ascending tendency,' which is in reality Gothic, and it is what is esteemed as Western religious architecture."[2] Though the inspiration for Milagrosa came from an engineering text, Candela designed each bay of Milagrosa by deriving it from his asymmetrical hypar umbrella forms (Figure 2). He started with an asymmetrical umbrella that is comprised of four straight-edged, hypar surfaces coming to a point at a column support (Stage 1). He then tilted it so that the short side rested on the ground (Stage 2), and then pulled up the middle of the short side to form a pointed triangle (Stage 3). This forms one half of a "bay" of the nave. By placing two of these forms back to back, Candela formed one full bay of Milagrosa. The nave of the church is comprised of four of these bays. The apse of the church is formed by another hypar, and the small side of the building is comprised of another eight smaller hypars. Adjacent to the small side, a series of folded plates form another roof covering (Figure 1).

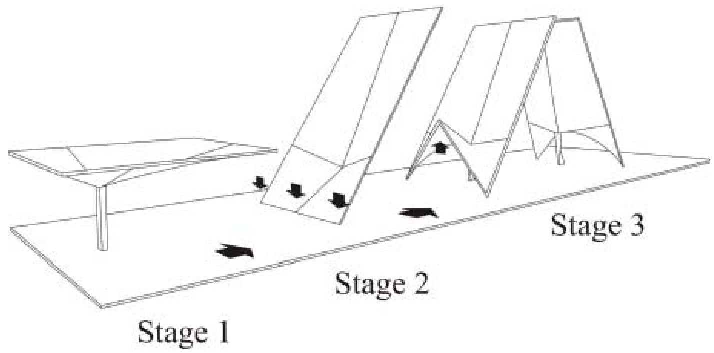
Candela designed Milagrosa with a primary focus on creating an exciting interior space using a structurally efficient form.[3] He shaped the columns both to better match the roof form and to counteract bending at the base that he anticipated (Figure 3). As he later realized, however, and as confirmed through a finite element analysis, there is negligible bending of the column.[1] Candela also added a thickening ridge at the top of Milagrosa, shaped with a scalloping pattern (Figure 4). The shell has a uniform thickness of 4 cm (1.6in) except at this ridge where it suddenly thickens to 14 cm (5.5in). Candela had calculated that there would be an upward vertical force at the top, which he counteracted by adding weight through this thickening ridge. When asked why he chose to add the weight on the exterior surface, he explained: "First, it is very easy to bring a weight over the top, and second, the form thereby looks more interesting from the exterior."[4] But Candela admitted, "Perhaps my consideration was false, perhaps the strengthening is superfluous. I was, moreover, at that time a beginner and had only worked with five or six constructions."[5] A finite element analysis presented in this paper reveals the effect of this thickening ridge.

Figure 1

The exterior of Milagrosa. [Photograph by Bruce White]

Figure 2

The design concept for Milagrosa. Based on a drawing appearing in Faber, *Candela* (1963).



Analysis

This analysis of Milagrosa can be broken down into three studies: 1) a study of the three individual stages of the design concept, 2) a continuity study that considers Candela's design concept integrated as a half-bay of the church, and 3) an examination of the thickened, scalloped ridge. As previously discussed, Candela designed Milagrosa starting with one asymmetrical umbrella that he then tilted and warped. This final stage will be referred to as a half-bay (Figure 5). This analysis begins by studying each stage of this process through a detailed finite element analysis. Candela joined two of these half-bays together to create each bay of the nave. Following his design process, this paper undertakes a continuity study by first considering a full bay and then two adjacent bays. Finally, this paper examines the effects of the thickened scalloped ridge.

All analyses were performed using the Structural Analysis Program software package (SAP). Geometrically linear elastic behavior was assumed since the stress levels of the structure under dead load are well within the elastic range and out-of-surface displacements in the built structure are small. A mesh refinement study was performed to achieve reasonable convergence of displacements and stresses. The mesh used in these analyses includes 40 elements across the 6.8m width of the half-bay, with most elements having an aspect ratio of nearly one.

All three studies rely on the geometry of one half-bay which is derived from an elevation drawing by Candela (Figure 5). This half-bay is supported by 3 points: the column and two "feet." The geometry of the first two stages of the design concept was back-derived from this half-bay. Though in Milagrosa the height of the roof slightly increases with each bay, this study assumes a uniform geometry for all bays. In the design concept and continuity studies, the thickened, scalloped ridge is neglected and a uniform thickness of 4cm is assumed (1.6in). In the scalloped ridge study, the geometry of the ridge is defined by scaling points from an elevation drawing and a thickness of 14cm (5.5cm) is used in this region. All analyses are performed under the self-weight of concrete alone, assuming a density of 2400 kg/m^3 (150pcf). A conservative estimate of the compressive concrete strength equal to 1,406,000 kg/m^2 (2000 psi) is assumed.[6] ACI code indicates the rupture strength of concrete is 7.5 times the square root of the compressive strength. To make a conservative estimate, this paper will use 5 times the square root of the compressive strength as the rupture strength in tension: 154,700 kg/m^2 (220 psi). It must be considered in all of these analysis results that reinforcing steel was used in the shell so even if the rupture stress of the concrete is exceeded, the shell will function properly. All supports are modeled as fixed boundary conditions. The sign convention throughout the paper refers to tension as positive and compression as negative.

Stages of the Design Concept

The design concept for Milagrosa is one of the most captivating aspects of the final structure. To fully understand Candela's logic behind this concept, finite element analyses of each of the stages were performed as shown in Figure 6. The color scale at the bottom of the figures applies to all plots. The first column of this table shows the membrane stresses, which reflects only those stresses in the plane of the shell and neglects the effects of bending. The second and third columns show the maximum principal bottom and top stresses, respectively, which reflect the combined

Figure 3

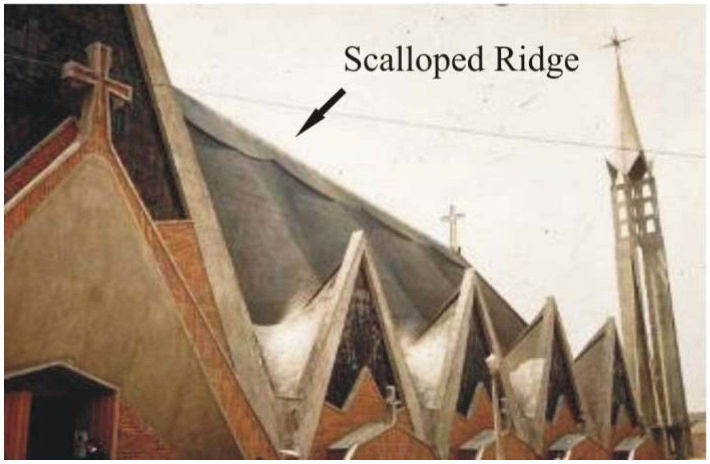
Photograph of interior showing column shaping. [Photograph by Bruce White]

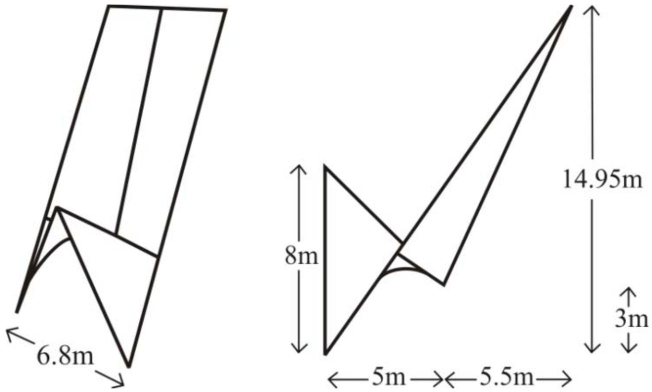
Figure 4

Early photograph of Milagrosa showing detail of scalloping ridge [Princeton University Candela Archives].

Figure 5

Dimensions of one half-bay.





effects of membrane and bending stresses. These plots show the maximum principal stresses (referring to the most positive numerical value where positive indicates tension), since tensile stresses are the most dangerous for thin shell concrete structures.

Figure 6 shows that all three stages reflect little difference between the membrane stresses and the bottom and top stresses indicating that bending is minimal in all three stages.

Stage 1 is predominantly in tension, with regions of tensile stress much higher than the conservative value of assumed rupture stress (notice the regions of dark blue). This high tensile stress would be expected in such an asymmetrical form. When Candela built asymmetrical umbrellas in practice, he thickened the shorter end to balance the self-weight of the longer end. For example At Ciba Laboratories, he used 4cm (1.6 in) lightweight concrete on the longer side and 20cm (7.9 in) regular weight concrete on the shorter side.[7] This use of thickened concrete for structural purpose foreshadows the thickened, scalloped ridge that he used in Milagrosa.

By tilting the asymmetrical umbrella in Stage 2, the high tensile regions (dark blue) are eliminated except for a few small regions on the edges (Figure 6d, e, and f). By then lifting the middle to form Stage 3, higher tensile stresses are present at the edges of the legs (Figure 6g, h, and i). Although there are small differences between the stresses in the top and bottom faces as compared to the membrane stresses in Figure 6g, overall the effects of bending are minimal and this paper can conclude that membrane effects dominate the behavior of the shell. Even though the bending effects are slight, it is clear that there is a small trend toward compression (more orange and red regions) in the bottom face and a small trend toward tension (more green regions) in the top face. The half-bay therefore acts as a tied cantilever where the column provides the upward vertical support and there is a downward reaction at the feet. Such behavior was confirmed by simple hand calculations.[8]

The following continuity study discusses how Candela dealt with these stresses. By examining this progression of form, it is clear how Candela's design concept moves from a highly tensile, unbalanced form to one which is largely within the rupture stress of concrete.

Figure 6

Finite element analyses of design concept. Images (a), (b), and (c) show the membrane stresses, the maximum principal bottom stresses, and the maximum principal top stresses, respectively, for Stage 1 (see Figure 2). Images (d), (e), and (f) show the stresses for Stage 2.

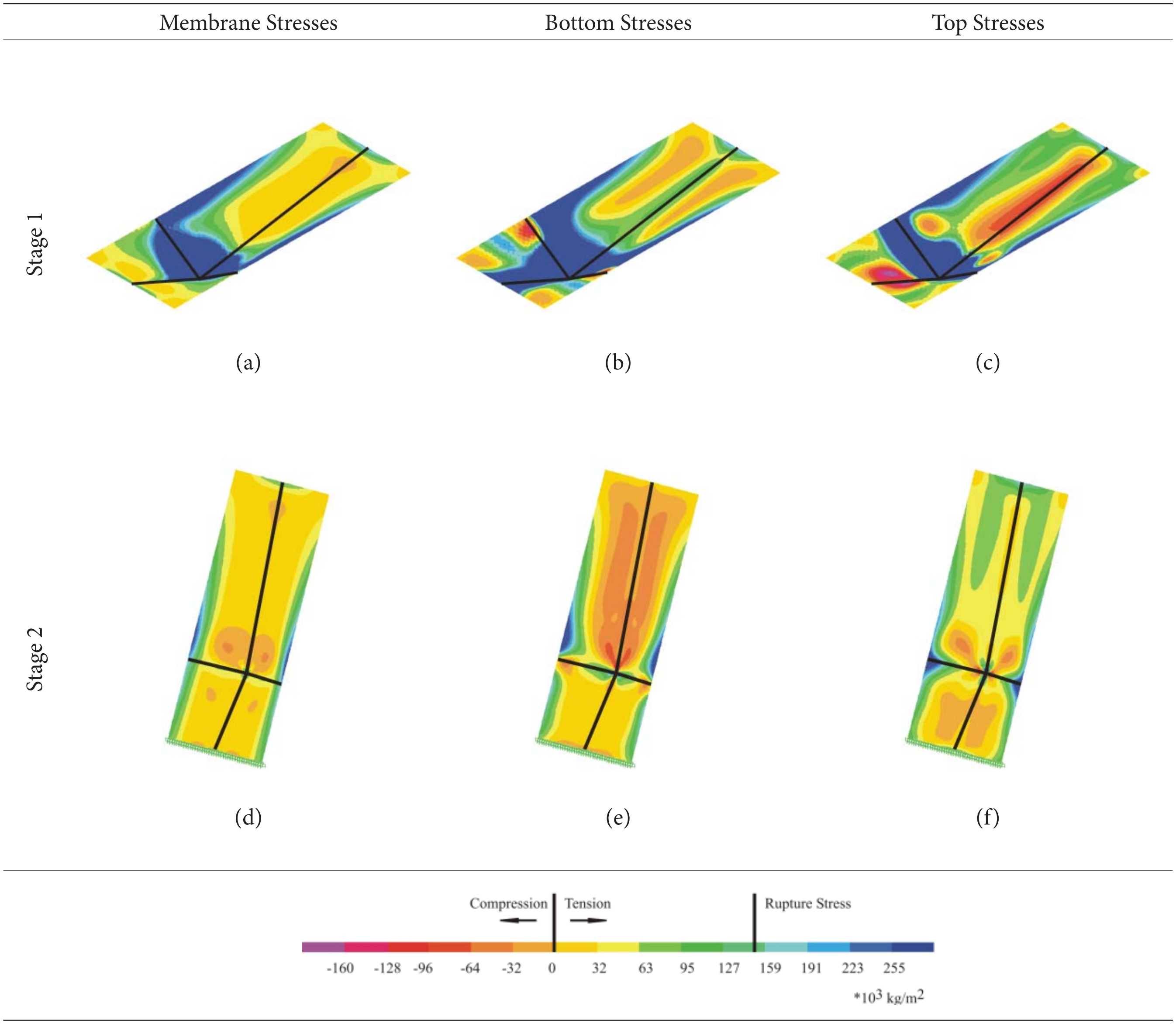


Figure 6 (continued)

Images (g), (h), and (i) show the stresses for Stage 3 as a half-bay.
Images (j), (k), and (l) show the stresses for Stage 3 as a full bay.

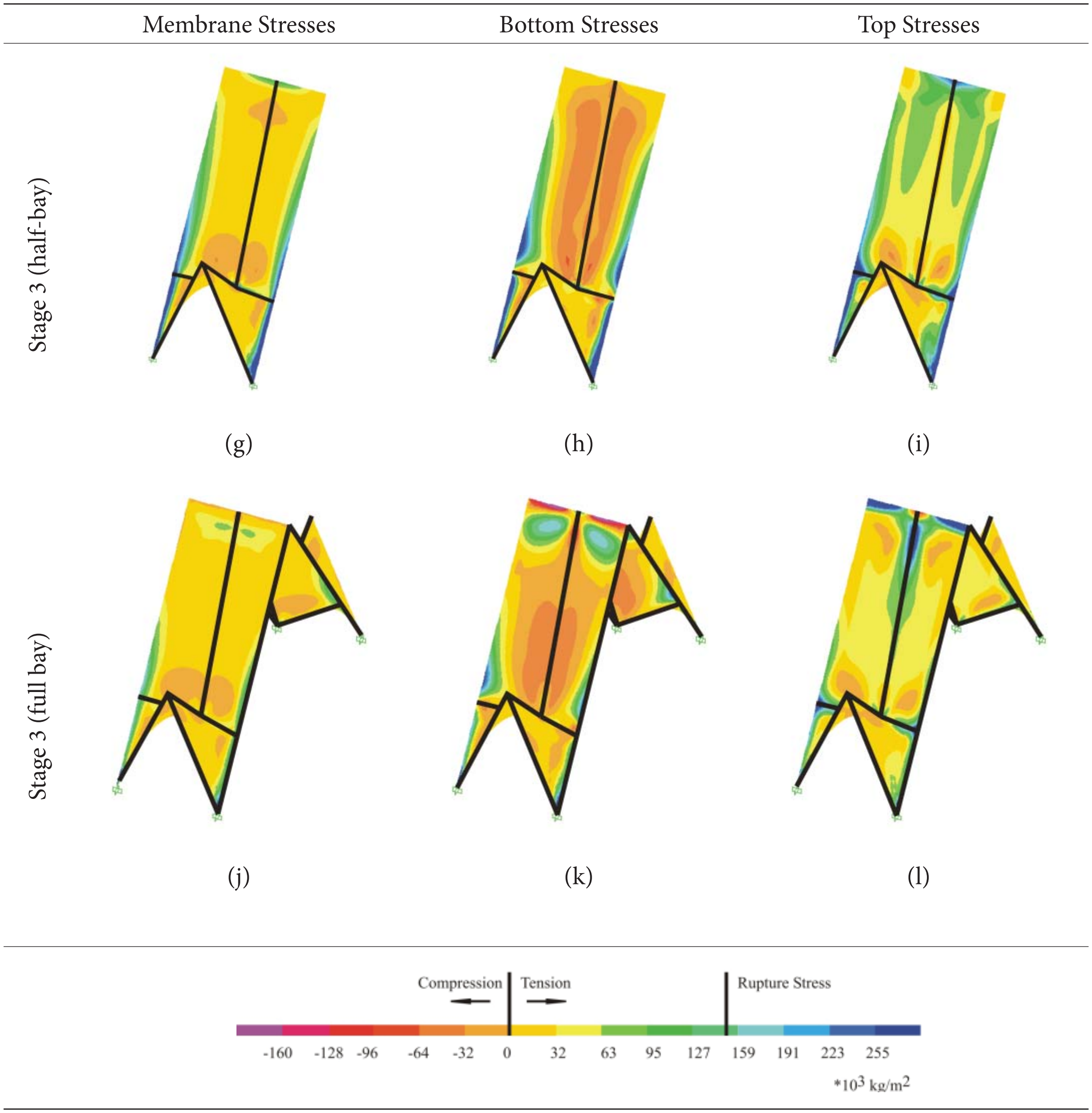
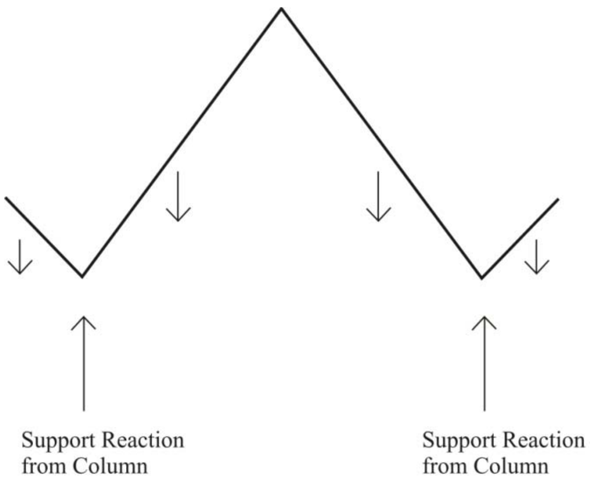


Figure 7

Schematic of full bay of Milagrosa.



Effects of Continuity

Candela placed half-bays back to back in Milagrosa, thereby allowing the forms to lean against one another. Finite element analysis on a full bay found that the leaning results in an upward reaction at the feet rather than the downward reaction that was found for the half-bay. This shows a fundamental change in the behavior of the form from acting like a tied cantilever to a three hinge arch (as conceptualized in Figure 7). When considering the stresses in the full-bay (Figure 6j, k, and l) and those in the half-bay (Figure 6g, h, and i), it is clear that there is not a drastic difference. However, the full-bay does slightly reduce the overall tension (green regions in the half-bay) in the top stresses and reduce some of the compression in the bottom stresses. Despite this advantage, large regions of tension (light and dark blue) appear at the top ridge of the full-bay analysis in both the top and bottom stresses.

While it is instructive to consider the half-bay and full-bay, Candela placed his bays adjacent to one other and it is crucial to look at the bays in this way to understand the overall load-bearing function of the structure. See Figure 8a and b for finite element analyses of four of these forms placed back-to-back and adjacent to one another, which comprise half of the Milagrosa nave. Note that the color scale at the bottom of Figure 8 applies to all plots.

Figure 8a and b show the maximum principal stresses on the bottom and top faces of the shell, respectively. The stresses throughout the shell are mostly low and uniform, ranging from about 32,000 kg/m^2 (46 psi) in tension to about the same in compression. This is low compared to the assumed conservative values for compressive strength and rupture stress of concrete. At the peak of the roof, where the two-half bays meet, a high compressive stress (shown in red) develops. However, this is still well within the compressive limit of concrete. Regions of tension develop in green and blue shades at the top and along the outer ridge which exceed the rupture stress. Overall, the shell is predominantly in tension, but the stresses are so low that most of the concrete, except those regions in blue, will not exceed the tensile capacity.

Other regions that exceed the conservative estimate of the rupture stress of the concrete are at the free edges near the support. At the support where the two full-bays join, however, the tension drops significantly, as indicated by the lack of blue regions that mark high tension (see Figure 8a). A small green patch remains between the two bays showing a small region of higher than average tension, but the stress is within the conservative estimate of the rupture stress. This shows that by placing the bays adjacent to one another, Candela was able to reduce the tension significantly. According to documentary photographs, the logic of his construction process called for the construction of at least two bays at once (Figure 9). See Garlock and Billington for a review of the construction process for Milagrosa.[9] Presumably, the tension at the exterior support would not have been of concern, since the forms appear adjacent to one another except at the ends, where they are framed by another hypar at the nave and by a stiffening triangle at the opposite end (see Figure 1). Candela placed additional reinforcement along the edges, presumably to take any tension that might occur if these edges were free during construction.

Figure 8

Finite element analysis of two bays. Images (a) and (b) show the maximum principal bottom and top stress contours, respectively, of the uniformly thick shell. Images (c) and (d) show the maximum principal bottom and top stress contours, respectively, of the shell with the thickened, scalloped ridge. Select values are highlighted.

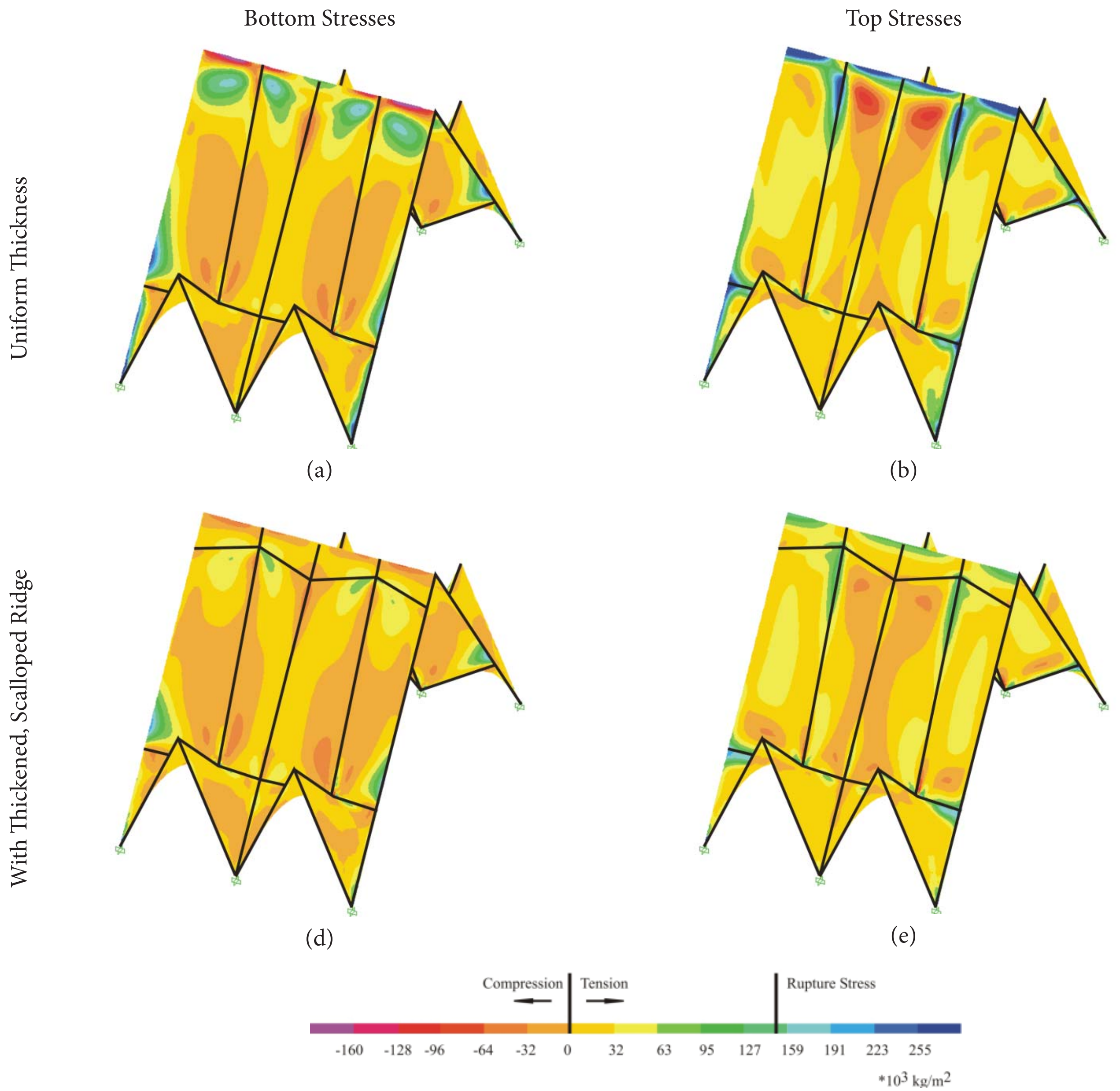


Figure 9

Construction of two bays. [Princeton University Candela Archives]

Effect of Thickened Scalloped Ridge

Though the effect of placing the forms adjacent to one another reduces the tension at the interior support, there is still significant tension at the top (as indicated by the blue regions in Figures 8a and b), which exceeds the conservative estimate of the rupture stress of concrete. Here, Candela added additional weight to the top by thickening the shell to 14 cm (5.5in). Figures 8c and 8d show the maximum principal stress distribution with this extra weight on top. By adding this weight, Candela reduced the tension at the top mostly within the rupture stress of concrete.

As shown in Figure 8d, there is one small region where the tensile stress exceeds the conservative estimate of the rupture stress. However, it does so by a small amount and it can be assumed that the steel reinforcing was sufficient to prevent the structure from cracking. This is the location where the scalloping ridge narrows within the valley of the half-bay. This narrowing is most likely reflective of Candela's aesthetic motivation and suggests his play of elegance within his discipline of form.

Another region of high tension is at the column support. Again, the tensile stress is high, but this time it well exceeds the assumed rupture stress. The addition of the scalloping actually makes this tensile stress slightly larger. However, this analysis modeled the column as a fixed, point support. In reality, Candela had a column there which widened to meet the hypar (Figure 3). Thus the column presumably reduces this tensile stress and brings the shell back within allowable limits.

Conclusion

Candela completed all drawings and office work in just two weeks and the construction of Milagrosa was completed in ten months. The structure encloses 1,533 square meters (16,500 square feet) and cost a total of $41,100 or $26.8 per square meter ($2.49 per square foot).[10] The general contractor for the project was Cubiertas Ala, and it was their first church commission. Arturo Sáenz de la Calzada signed the plans for Milagrosa, even though the design was entirely Candela's (Candela did not have an architect's license at the time).[11]

Candela's design concept shows his discipline and play with the hyperbolic paraboloid form. He begins with his asymmetrical "umbrella" – a form with which he had already had great success. By tilting and warping this form through the stages shown in Figure 2, he develops an entirely new and surprising structure.

This analysis showed how his design concept develops from a simple cantilever to a tied cantilever to a three hinge arch. By placing these bays adjacent to one another, tensile stresses at the support are significantly reduced.

Finally, finite element analyses of the structure with and without the thickened, scalloped ridge (Figure 4) revealed that the added weight of the thickening reduces or eliminates tension on the shell (as Candela predicted). The scalloped ridge therefore serves a structural function first and an aesthetic one second.

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DAVID P. BILLINGTON
Highlights of an Engineering Life

1927 Born in Bryn Mawr, Pennsylvania. Father Nelson Billington was an insurance broker, mother Jane Coolbaugh Billington was a writer for Curtis Publishing in Philadelphia. Two brothers, James (b. 1929), and John (b. 1941).

1945-46 Served in the U.S. Navy as a Radar Technician.

1946-50 Attended Princeton University and with the encouragement of Dean Kenneth Condit studied Basic Engineering, which allowed many humanities courses in addition to covering mechanical, electrical, chemical, and aeronautical engineering. Graduated in the Class of 1950 with the degree of Bachelor of Science in Engineering.

1950-51 Awarded a Fulbright Fellowship for one year to study civil engineering at the University of Louvain (Leuven) in Belgium. Met and began to date Phyllis Bergquist, also on a Fulbright Fellowship studying piano at the Royal Conservatory in Brussels. Married Phyllis in Chicago on August 26, 1951. Six children born from 1953 to 1968: David, Elizabeth, Jane, Philip, Stephen, and Sarah.

1951-52 Fulbright Fellowship to Belgium renewed for one year. Studied under Gustave Magnel and studies included bridge construction, structural design theory, and prestressed concrete.

1952-60 Worked as a structural designer in the New York office of Roberts and Schaefer. Mentored by Anton Tedesko, performed calculations for the structure of the St. Louis airport terminal, helped lay out the Northwest Expressway (now Interstate 190) near Chicago, and designed a hangar for Hill Air Force Base in Ogden, Utah, the longest-span prestressed concrete roof in the United States at the time (1958). Member of a delegation to observe concrete construction in the Soviet Union (1958). Designer and project manager of Pier 40 in New York and Launch Complex 36 at Cape Canaveral.

1960 With the support and mentoring of Professor Norman Sollenberger, began teaching part-time at Princeton in 1958 and full-time in 1960 as an Associate Professor in the Department of Civil Engineering. Supervised doctoral students and promoted to Professor in 1964.

1961 In addition to teaching civil engineering full-time, taught architecture graduate students (1961-1995). Director of the Program in Architecture and Engineering (1990-2008).

1965 Published *Thin Shell Concrete Structures* (1965), reprinted in 1982. Named one of the 25 McGraw-Hill Classic Text Reprints in 1989.

1966-67 National Science Foundation Fellowship to study with W.T. Koiter and (informally) with A.L. Bouma at the Technical University of Delft, Netherlands. Family lived in The Hague for six months.

1969-72 Organized “Summer in Engineering” program at the Princeton engineering school for minority youth in the Princeton community. Program merged with a summer camp in Blairstown, New Jersey.

1960s Architecture graduate students suggested including examples of beautiful works such as those of the Swiss engineer Robert Maillart. Visited Switzerland summer 1970 and many summers thereafter to photograph and research the works of Maillart and other Swiss structural artists.

1970-72 With support from the National Endowment for the Humanities, organized a first Conference on Engineering and the Humanities (1970) with Robert Mark and a second Conference (1972) with Robert Mark and John Abel. Second conference brought together structural engineers Christian Menn, Fazlur Khan, and Felix Candela, who acknowledged the influence of Maillart on their works integrating efficiency, economy, and elegance. Conferences and exhibitions at the Princeton Art Museum followed on the Eads Bridge (1974), the Bridges of Maillart (1976) and Menn (1978), and the works of Heinz Isler (1980).

1970s-90s Consultant to private industry on the design of thin-shell cooling towers and other structures, consultant to state governments on bridge design and traffic safety. Invited to visit Japan and provide an aesthetic evaluation of recent Japanese bridges (1989). Consulted for the Millau Viaduct (1990s), France.

1973-74 Princeton Maillart Archive founded.

1974- Began to teach CIV 262, now CEE 262, "Structures and the Urban Environment," an introductory course presenting the ideals and tradition of modern structural art through great works of 19th and 20th century structural engineers. Follows the approach of an art history course to teach liberal arts and engineering students key bridges and buildings and their designers through numerical exercises, narrative readings, and slide visuals. Course is now directed by Maria Garlock.

1978-79 As a visitor to the Institute for Advanced Study in Princeton, wrote *Robert Maillart's Bridges* (1979), which received from the Society for the History of Technology the 1979 Dexter Prize for Outstanding Book.

1978-85 Chairman of the Committee on Aesthetics in the Design of Structures, American Society of Civil Engineers.

1983 Publication of *The Tower and the Bridge: The New Art of Structural Engineering* (1983), making the case for the best works of modern structural engineering as an art form and tradition distinct from modern architecture.

1985- Began to teach CIV 102, "Structures and Machines," an introductory slide lecture course on great events in American civil and mechanical engineering. Course soon added electrical and chemical engineering and is now CEE 102 "Engineering in the Modern World." Liberal arts and engineering students learn the key innovations and innovators in American history through numerical exercises, narrative description, and slide visuals. Course is now directed by Michael Littman.

1986 Elected Member of the National Academy of Engineering. Received the History and Heritage Award of the American Society of Civil Engineers.

1987-93 Andrew D. White Professor-at-Large, Cornell University.

1989-91 With the support of President Harold Shapiro and the Council on Science and Technology, CEE 102 and CEE 262 courses receive university-wide credit.

1990 Received the Charles A. Dana Award for Pioneering Achievement in Education from the Dana Foundation in New York. Conferred the degree of Honorary Doctor of Humane Letters from Union College, Schenectedy, New York (1990). Conferred the degree of Honorary Doctor of Science from Grinnell College, Grinnell, Iowa (1991). Carnegie Endowment for Teaching New Jersey State Professor of the Year (1995). Conferred the degree of Honorary Doctor of Engineering from the University of Notre Dame, Notre Dame, Indiana (1997).

1992 Eleven grandchildren born 1992-2005: Zoe, Timothy, Susannah, Lucy, Francesca, Rachel, Roy, Daisy, Anna, Clara, and Bram.

1995 Received, as joint author with Jameson W. Doig, the Ussher Prize from the Society for the History of Technology for Best Scholarly Article, for "Ammann's First Bridge: A Study in Engineering, Politics, and Entrepreneurial Behavior," *Technology and Culture* (January 1994).

1996 Publication of *The Innovators: The Engineering Pioneers Who Made America Modern* (John Wiley and Sons, 1996).

1997 Publication of *Robert Maillart: Designer, Builder, Artist* (Cambridge University Press, 1997), culminating three decades of study on the Swiss master builder and structural artist.

1998 Elected Fellow of the American Academy of Arts and Sciences and Honorary Member of the American Society of Civil Engineers (1999). Also elected Honorary Member of the American Concrete Institute (2003) and the International Association of Shell and Spatial Structures (2004).

1999 Honored by *Engineering News-Record* as one of the top five civil engineering educators since 1874.

1999 Awarded the Sarton Medal and holder of the Sarton Chair, University of Ghent, Belgium (1999-2000).

2000 Exhibit on *The New Art of Structural Engineering*, NSF Art of Science Project, National Science Foundation, Arlington, Virginia. On exhibit in the NSF Engineering Directorate, 2000-2006.

2003 Symposium in Honor of 45 Years of Teaching, attended by colleagues and former students, coinciding with publication of *The Art of Structural Design: A Swiss Legacy* (Princeton Art Museum/ Yale University Press, 2003), and an exhibition of the same title at the Princeton Art Museum. Exhibition traveled USA, Canada, and Switzerland.

2003 National Science Foundation Director's Distinguished Teaching Scholar Award.

2004-05 Summer workshops held for faculty from twenty other colleges and universities to introduce the ideas and approach of CEE 262 and CEE 102. Supported by the National Science Foundation (2004) and the Carnegie Foundation (2005).

2006 Publication, as joint author with David P. Billington Jr., of *Power Speed and Form: Engineers and the Making of the Twentieth Century* (Princeton University Press, 2006); and as joint author with Donald C. Jackson, of *Big Dams of the New Deal Era: A Confluence of Engineering and Politics* (Oklahoma University Press, 2006).

2006 Robert Noyce Visiting Professor, Grinnell College, Grinnell, Iowa.

2007 Keynote Lecture, Conference on Fracture Mechanics, Catania, Sicily. Return visit with Phyllis Billington to Taormina, Sicily, which David and Phyllis visited together as Fulbright students.

2008 Morison Prize Lecture, Massachusetts Institute of Technology, and endowed lectures at Harvard, Yale, and Wellesley Colleges. Received the 2008 Distinguished Award of Merit from the American Council of Engineering Companies. Lecture to the METRANS Transportation Center, University of Southern California.

2008 Publication, as joint author with Maria Garlock, of *Felix Candela: Engineer, Builder, Structural Artist* (Princeton Art Museum/Yale University Press, 2008), and an exhibition of the same title at the Princeton Art Museum. Exhibition traveled USA.

2009- Keynote Lectures: Conference of the IASS, Valencia, Spain (2009), Rensselaer Polytechnic Institute, Troy, New York, on the 175th anniversary of their civil engineering program (2010), and Construction History Congress, Philadelphia (2010). Lecture at the University of Toronto (2011) and Fazlur Khan Lecture at Princeton University (2011). Keynote Lecture on Heinz Isler, IABSE/IASS Conference, London (2011) and on Felix Candela, Columbia University (2012). Plenary Address to the ASCE/SEI Structures Congress, Chicago (2012).

2009- First meeting in Princeton of network of graduate alumni and colleagues, now the International Network for Structural Art. Meetings held in 2011 and 2012.

2010 Recorded interview by Crosby Kemper at the Kansas City Public Library with brother James H. Billington, Librarian of Congress, on the humanities as seen through both history and engineering.

2010 One in four undergraduate students at Princeton takes either CEE 262 or CEE 102 by the time they graduate.

2010 Retirement from fifty years of full-time teaching at Princeton University celebrated by a departmental dinner and a symposium of former students.

2011 Sixtieth Wedding Anniversary of David and Phyllis Billington.

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