Integrating Green and Resilient Building Design for Enhanced Disaster Recovery

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ABSTRACT

Worldwide urbanization correlates to growing vulnerability to seismic and other natural hazards. Integrated performance-based design and assessment of green and hazard-resilient buildings can offer innovative alternatives for urban disaster recovery. We propose a life cycle assessment methodology that links the distinct fields of sustainability and hazard-resilience to advance building design and identify leverage points for improved disaster mitigation and recovery. Our "green-resilience" framework can be used to analyze the implications of disaster reconstruction, quantifying environmental metrics and socio-economic indicators of building performance over its lifetime. Two examples illustrate the framework's utility: (1) a design and seismic assessment of a hypothetical commercial building in Los Angeles, CA, U.S.A.; and (2) a qualitative discussion of its use guiding reconstruction decisions in Christchurch, New Zealand.

Introduction

As recent events like the 2010-2011 Canterbury, New Zealand earthquakes show, a holistic approach to disaster mitigation, planning and recovery is needed to reduce losses of human life, urban infrastructure, and natural ecosystems. In current thinking, the built environment's ecological and health impacts and its hazard resilience are often treated separately, despite their mutual roles in vulnerability, recovery and resilience. Philosophies for green building design and hazard-resistant design each seek to optimize building performance, but for different criteria. Green building techniques attempt to mitigate the threats to human health and degradation of the natural environment associated with the construction and use of buildings through efficient use of water, energy and material resources. Hazard-resistant design meanwhile aims to satisfy objectives for performance in design-level hazard events, which are related to different levels of post-disaster functionality. But resistance alone does not equate to recovery, and in recent years engineering focus has turned more to hazard-resilient design: robust, redundant structures that adapt creatively to hazard-induced damage and losses, with limited loss of post-disaster functionality [1].

This study describes a new life cycle "green resilience" framework for investigating the integrated environmental impact and seismic vulnerability of buildings to enhance building design for improved post-disaster outcomes.

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Welsh-Huggins SJ, Liel AB. Integrating green and resilient building design for enhanced disaster recovery. *Proceedings of the 3rd International Conference on Urban Disaster Reduction*, Earthquake Engineering Research Institute, Boulder, CO, USA, 2014.

Framework for Green-Resilience

This paper presents an innovative framework for integrated life cycle assessment of a building's environmental impact and hazard resistance. The framework assesses building performance through four stages: design, analysis, assessment, and adoption (Fig. 1). The analysis stage includes structural analysis of the hazard performance of the building, loss estimation quantifying potential economic losses from repair needs, and environmental analysis of life cycle building impact. In the future, feedback loops may be added to help identify specific building vulnerabilities that could hamper post-disaster recovery or worsen environmental degradation. The framework's proposed green-resilience integration tool offers a user-friendly graphical interpretation of results, with building performance color-coded on a scale ranging from good to poor performance.

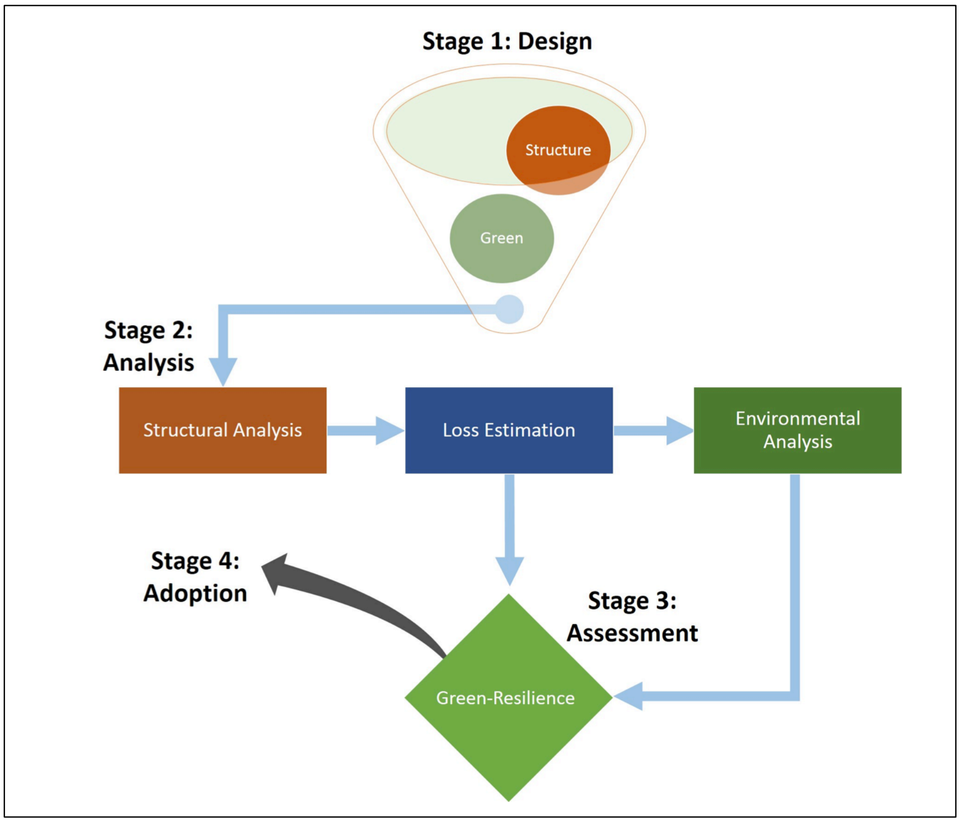

Figure 1. Proposed framework for integrating environmental impact with hazard vulnerability in assessing the life cycle effects of building performance.

Two case studies illustrate the "green-resilience" framework. The first presents the results of analysis of a new commercial building in Los Angeles designed with and without a green roof; the second discusses the framework's utility as it could be applied during the reconstruction of Christchurch, New Zealand. In this trial implementation, we present the building green-resilience life cycle assessment in four categories of metrics, two each to describe hazard performance and environmental impact: repair cost, material damage, fossil fuel consumption, and climate change potential. Repair cost represents the dollar value of all needed repairs and replacements after an earthquake, compared with the potential cost of replacing the entire building. Material damage describes the severity of losses in the most-damaged structural or non-structural component, as a ratio of the number of damaged units to the total units (damaged and undamaged). Climate change potential (tons of CO_2 equivalents) quantifies the amount of greenhouse gas emissions released during a building life span. Fossil fuel consumption (mega-joules, MJ) acts as a proxy for total primary energy consumed during the building life cycle. Improved green-resilience performance is inferred from lower repair costs, fewer damaged material quantities, and lower fossil fuel consumption and climate change potential.

Case Studies

Case Study 1: Assessment of a Building with a Green Roof

The life cycle performance of a building—both in terms of its hazard-resistance and its environmental impact—is an important consideration during the design phase of a new project. The first case study illustrates how considering the life cycle effects of a building can reduce both potential post-disaster losses and environmental degradation from added building repairs.

Stage 1, Design, provides a platform for engineers and architects to work together to create a building design that meets both hazard-resistance and sustainability performance objectives. As discussed above, green building features can help to reduce impact on the environment or human health through less-resource intensive use of water, energy, and other materials. In this example, we consider a four-story commercial building in southern Los Angeles, designed with and without a green roof. The reinforced-concrete building uses a special moment-resisting frame system to meet codified standards for seismic design [2]. The green roof is composed of light grasses and four inches of soil overtop the roof system and reduces stormwater runoff. The heavier dead load of the saturated soil required larger column and beams for the green roof building.

Stage 2, Analysis, is composed of structural analysis, loss estimation, and environmental analysis. For the structural analysis step, we used the *OpenSEES* seismic analysis program to conduct a nonlinear analysis of a two-dimensional, three-bay model of each building. Subjected to increasing levels of seismic intensity, both experienced greater interstory drifts at higher ground motion intensities. At each intensity level, the larger beams and columns of the green roof building resulted in lower interstory drifts than the non-green roof building.

For the loss estimation, we used the *Performance Assessment Calculation Tool* (PACT), to integrate building usage, structural and nonstructural components, collapse potential, and results of structural hazard analysis into predictions of needed seismic repairs and associated costs [3]. In both buildings, damage concentrated in the interior partitions and increased with at higher levels of seismic shaking. At all intensity levels, the larger member sizes required for the green roof building resulted in better seismic performance (i.e., lower seismic losses) than the control model.

In the environmental analysis, we consider a building life cycle of material extraction, product manufacturing, material transportation to site, construction, operation, maintenance and repairs, and end-of-life [4]. Crucially, the buildings' operations and maintenance (O&M) stage is expanded to include repair and reconstruction after earthquake-induced damage, on top of routine maintenance actions. The product-based life cycle tool ATHENA Impact Estimator [5] was used to assess the environmental impact over 60 years for both buildings. We first considered a baseline scenario for each building in which the life cycle environmental impacts were calculated assuming an earthquake or other hazard event does not occur during the building lifespan. Next, we created alternate life cycle scenarios for each hazard level. In each additional scenario, the impact of new material production for post-earthquake repairs and replacement was added to the O&M stage to quantify the added environmental burden.

Stages 3 and 4, Assessment and Adoption, allow the design team to assess the life cycle performance of the building and improve the design based on the results, before adopting a final design for construction. The results of the green roof study suggest that as ground shaking intensity increases, greater damage occurs, leading to more structural and nonstructural repairs. These repairs increase climate change potential and fossil fuel consumption, such that the CO_2 released and the fossil fuel consumed for each alternative analysis case increases with greater level of seismic excitation. Fig. 2 presents a preliminary graphical representation of the integrated building performance for sustainability and hazard-resilience. In the context of hazard resistance, the performance color in each category indicates the severity of damage and material losses. The performance color assigned to the environmental metrics illustrates the proximity of building impacts to baseline estimates. These comparisons lead to the final stage, Adoption, where the results will help design teams identify design changes for structural or building system components, to produce a structure that is high performing across all categories.

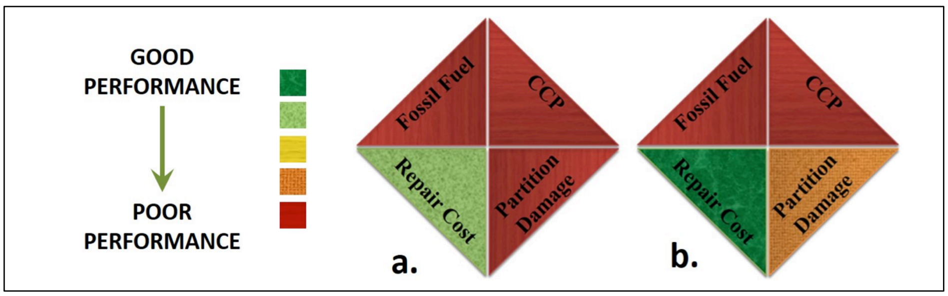

Figure 2. Integrated green-resilience life cycle assessment results for a) building without a green roof, subjected to moderate earthquake shaking, and b) building designed with a green roof, at the same hazard level. More partition damage in the control building resulted in higher repair costs. Post-earthquake repairs in both buildings led to large Fossil Fuel Consumption and Climate Change Potential (CCP) environmental burden.

Case Study 2: Assessment of New Construction in Christchurch, New Zealand

The second case study offers a theoretical discussion of the framework's implementation in new construction in Christchurch, New Zealand, as rebuilding continues after the 2010-2011 earthquakes. The weeks and months after a disaster are an important time period within which to make changes to building codes and design practice, with the consequences of vulnerability forefront in public memory [6]. Adopting the holistic design approach for new buildings suggested by our green-resilience framework would support Christchurch in meeting its goals for a "green city" with a "stronger built identity" [7].

Stage 1, Design, of this building has already occurred. This example considers the new Forte Health hospital building in Christchurch, which was designed to include both innovative features in sustainability and seismic performance. The hospital is the first new building since the earthquakes to obtain a 4 Star Green Star rating. Green features include a high-efficiency heating and cooling system, low-energy LED lighting, and water efficient fittings throughout the building. The innovative PREcast Seismic Structural System (PRESS) includes a post-tensioned steel rocking system to better resist shaking of extreme seismic events. Back-up generators and a potable waters system aim to provide ongoing functionality after future disaster events [8].

Stage 2, Analysis, is presented here as a hypothetical discussion of the possible outcomes of analysis. Our structural analysis would conduct a nonlinear analysis at varying levels of seismic intensity. Stated to be 80% stronger than required by New Zealand code, analysis should test its performance during ground motions that represent severe rare, high-magnitude shaking.

The results of the structural analysis inform the loss-estimation stage, identifying potential vulnerability areas of the building and quantifying subsequent economic costs from post-earthquake repairs. A key step in loss-estimation is calculating the likelihood that each type of building component experiences a particular damage state as a function of structural response [9]. Given the uniqueness of the PRESS system, experimental testing could be used to develop predictions of the probability that the system could fail under extreme loading conditions. Environmental analysis of the building life cycle will likely indicate that the high-efficiency heating and cool systems provide long-term reductions in climate change potential and fossil fuel consumption. The ability of the PRESS system to ensure post-earthquake functionality of these non-structural components, however, will greatly influence the true life cycle impact of the building. Although the design is touted for its sustainability considerations, damage to these systems could require material and energy-intensive production for replacement and repairs.

Stages 3 and 4, Assessment and Adoption, will evaluate the tradeoffs and benefits of this new design. Innovative buildings such as the Forte Health hold the potential to revolutionize urban disaster recovery and long-term environmental health. The large upfront costs typically associated with such design-choices may be prohibitive to potential investors, however, if higher life cycle performance is not compared against a representative baseline scenario. Formalizing objective baseline references will provide measurable outcomes for environmental impact and hazard damage. A sensitivity analysis would help to determine cutoff points for the performance levels at different hazard cases, when compared against baseline values.

Conclusions

This framework presents an innovative methodology through which engineers and architects can better assess and plan for the complex interactions and tradeoffs between building hazard resistance and sustainability through building design and modeling, structural and environmental analysis, and life cycle assessment. With urban hazard vulnerability increasing, the environmental impact and hazard performance of buildings must be considered in tandem. The prosperity of a city will depend on its harmonious, not harmful, interactions with the natural environment, and its ability to not just withstand hazard events, but to adapt from them.

Acknowledgements

This research is supported by the National Science Foundation. Funding is provided by NSF Grant Number 1234503.

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