

Lessons Learned from Seismic Collapse Assessment of Buildings for Evaluation of Bridge Structures

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ABSTRACT

Due to recent advancements in performance-based earthquake engineering methods, in modeling of complex nonlinear structural behavior, and in characterization of earthquake ground motions, it is becoming possible to directly simulate earthquake-induced structural collapse. These simulations can be used to develop probabilistic descriptions of structures' seismic collapse risk. This paper first summarizes recent developments in assessment of seismic collapse risks for building structures, which apply nonlinear time-history analyses to predict when structural collapse occurs. In the second part, the discussion focuses on how the lessons learned from these building collapse risk assessments can be applied to predicting the seismic collapse risk of bridge structures. The paper proposes extending current assessments of bridge seismic performance (which typically focus on prediction of structural damage prior to collapse) to include robust assessments seismic collapse safety. Key issues for structural collapse assessment relate to ground motion scaling and spectral shape, creation of nonlinear structural simulation models (differing in certain critical characteristics from models used to predict pre-collapse response), and incorporating uncertainties in ground motions and structural modeling.

INTRODUCTION

A primary goal of seismic design and code provisions is the protection of public safety in future earthquakes, implying that structures should have a relatively low likelihood of earthquake-induced collapse. However, the seismic collapse risks of building and bridge structures are in general unknown and quantitative data of collapse risks are not available to calibrate code and design decisions. Moreover, evidence from past U.S. earthquakes suggests that certain structures may be particularly vulnerable to earthquake-induced collapse, including those designed and constructed before significant advancements in understanding of seismic design and assessment in the mid-1970s (e.g. nonductile concrete bridges and buildings) and those with unique design characteristics (e.g. buildings with strength and stiffness irregularities, skewed or discontinuous-span bridges). The relatively moderate Northridge earthquake damaged thousands of buildings and damaged 228 bridges, collapsing six (all designed before 1974) (Basoz et al. 1999).

Recognizing the importance of protecting against and quantifying risks of earthquake-induced collapse, researchers at the Pacific Earthquake Engineering Research (PEER) Center, the Applied Technology Council (ATC) and elsewhere have developed procedures for prediction of seismic collapse risks, within the broader framework of performance-based earthquake engineering (Deierlein 2004). Direct prediction of seismic collapse relies on sophisticated nonlinear analysis models

capable of capturing deterioration in strength and stiffness as a structure collapses, robust convergence algorithms, and methods for incorporating uncertainties related to ground motions characteristics and modeling. The metrics of seismic collapse risk obtained through this process are potentially very useful – for comparing safety of different buildings or type of buildings, identifying particularly vulnerable existing structures as candidates for retrofit, or for evaluating and improving seismic design provisions. A particularly important application is the FEMA-sponsored ATC-63 project, which establishes a methodology whereby performance-based assessment of collapse risk is used to evaluate the adequacy of seismic code provisions proposed for new structural systems (ATC 2008b).

This paper describes the state-of-the-art in seismic collapse assessment of buildings, using recent research by the authors on seismic collapse risks of older (existing) and modern reinforced concrete (RC) frame buildings as a case study. Considerations related to selection of buildings for assessment, creation of nonlinear simulation models, ground motion characterization, incremental dynamic analysis, incorporation of modeling uncertainties and interpretation of metrics of collapse risk are discussed. Lessons from seismic collapse assessment of buildings are used to make the case for a systematic assessment of collapse risk of bridge structures, taking advantage of recent developments in seismic assessment of buildings and bridges.

SEISMIC COLLAPSE ASSESSMENT OF BUILDINGS

The general procedure developed for assessing the seismic collapse risk of building structures is described below. Case studies include collapse assessments recently conducted by the authors for a set of older (non-ductile) RC frame office buildings, of particular interest because of their suspected vulnerable to earthquake-induced collapse, and a comparable set of modern (ductile) structures (Haselton and Deierlein 2007; Liel and Deierlein 2008). Other research assessing risks of earthquake-induced building collapse includes Lignos et al. (2008) for steel moment frames, Christovalis et al. (2008) for light wood frame buildings and Zareian and Krawinkler (2007) for generic wall and frame structures.

Archetype Buildings for Assessment. Seismic collapse assessment may be conducted for an individual building of particular interest. Given the complexity of the methods, these assessments are most likely warranted for large or important structures. In these cases, the building can be modeled and analyzed according to existing design drawings. Of course, we may also wish to assess the seismic collapse performance of a particular class of structures, such as nonductile RC moment frame structures, rather than an individual building. In this case, the concept of *archetype* buildings facilitates the assessment by limiting the assessment to a set of buildings, called archetypes, selected to be representative of typical structures of the class of interest (ATC 2008b; Haselton and Deierlein 2007; Liel and Deierlein 2008). The number and characteristics of the archetypes depend on the structural system of interest but should include variations in the key design parameters expected to affect seismic collapse performance. In the assessment of nonductile RC moment frame structures, selected archetypes vary in terms of height (2 to 12 stories) and framing system (space and perimeter frame structures).

Nonlinear Simulation Models. Direct simulation of collapse requires analysis models for archetype structures that are capable of predicting nonlinear behavior as the structure becomes damaged and collapses in an earthquake. Models for each structural component should simulate likely modes of strength and stiffness degradation that may occur. Previous research has shown that accurate calibration of component strength and deformation capacity is particularly important for predicting collapse (Ibarra et al. 2005; ATC 2008a). A component backbone used to model lumped plasticity RC columns for predicting collapse is shown in Figure 1; model parameters related to strength, stiffness and deformation capacity (shown as $\theta_{cap,pl}$) are a function of reinforcement design and axial loads and have been calibrated to results from more than 250 column tests (Haselton et al. 2008). The choice of models depends on their ability to simulate the critical failure modes of the system.

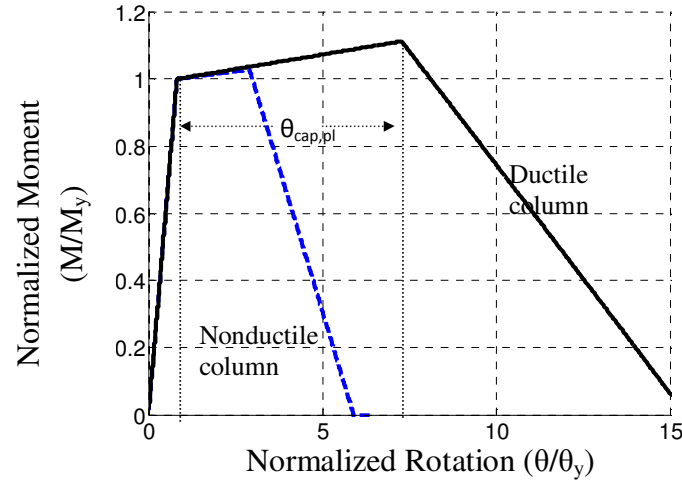


Figure 1. Properties of inelastic springs used to model typical RC columns, showing differences in deformation capacity for nonductile and ductile columns important for predicting collapse.

Nonlinear component models are combined into a system-level model that can predict likely sidesway and vertical collapse mechanisms. These models may be two or three-dimensional, depending on the collapse behavior expected. Geometric nonlinear (P-Delta) transformations are essential for predicting the large deformations precipitating collapse (Ibarra et al. 2005). Soil-structure interaction may be important for relatively stiff buildings and for bridges. A two-dimensional model used to simulate collapse of RC moment frame systems in OpenSees is illustrated in Figure 2.

Certain failure modes may be difficult or impossible to accurately represent in the analysis model and excluding these failure modes will lead to an underprediction of collapse risks. These collapse modes can be incorporated indirectly into the assessment by defining collapse as occurring when a particular component limit state is exceeded in dynamic analysis (Liel and Deierlein 2008). Definition of the component limit states associated with collapse is based on available experimental data. For example, in the collapse assessment of nonductile RC frame buildings, vertical collapse associated with loss of gravity-load bearing capacity in columns is difficult to directly simulate because of the limited data for model calibration (Liel and Deierlein 2008; Elwood 2004). Instead, sidesway collapse is simulated from the nonlinear analysis model and vertical collapse is triggered if the column deformations

during the dynamic analysis (demand) exceed a specified level defined by component fragility functions for RC columns (capacity) (Liel and Deierlein 2008). Although indirect incorporation of nonsimulated collapse modes is not ideal it enables assessment of systems that are difficult to simulate.

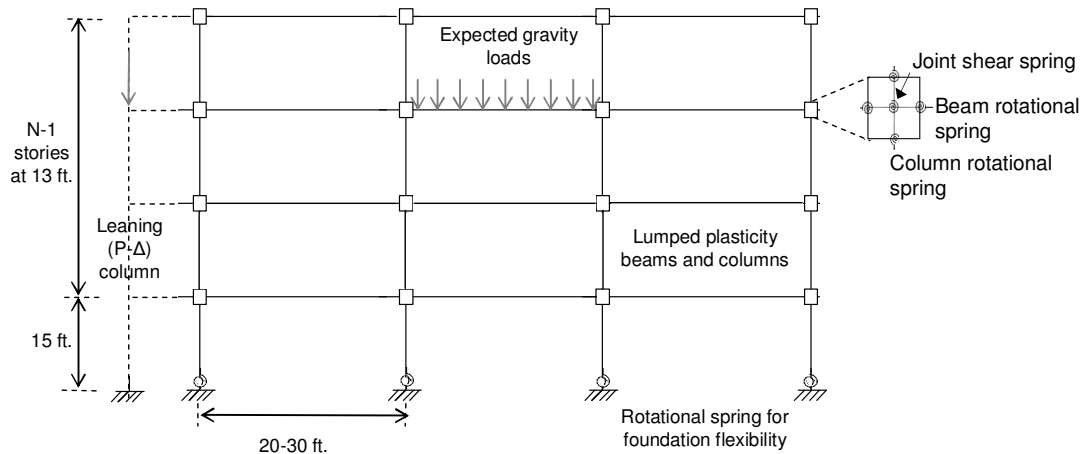


Figure 2. Schematic illustration of nonlinear analysis model for predicting earthquake-induced collapse of RC frame archetype buildings.

Ground Motion Characterization and Seismic Hazard. Collapse simulation requires dynamic analysis of nonlinear building models. Selection and treatment of ground motion records for use in dynamic analyses is a major topic of research. The ground motions used for the structural analyses should accurately represent (to the extent possible given current knowledge) the ground motions expected at the building site, with specific focus on the expected intensity level and frequency content (spectral shape) of the motions. For a site-specific assessment, i.e. when the location of the building and local seismology is known, disaggregation of the seismic hazard can be used to select or simulate ground motions which reflect the earthquake magnitudes, site-source distances, and epsilon values (which are related to spectral shape) that are representative of the site and hazard level of interest (Haselton et al. 2008). In other cases, a more generic ground motion set may be used. For example, the ATC-63 project selected a set of 22 pairs of recorded ground motions that are representative of large magnitude earthquakes and recorded at moderate fault-rupture distances, but without near-field directivity effects; details of the selection procedure are described elsewhere (ATC 2008b). Synthetic records are often used in the central and eastern U.S., due to the lack of recorded ground motions in that region. When general ground motion sets are utilized, spectral shape (epsilon) must be carefully accounted for, as described below.

The intensity of a ground motion is frequently quantified in terms of the spectral acceleration at the first-mode period of the building, $S_a(T_1)$.¹ The expected severity of ground-shaking at a particular site may be represented by a site-specific hazard curve, obtained through probabilistic seismic hazard analysis (Haselton et al. 2008).

¹Other intensity measures may be used (including peak ground acceleration, spectral displacement, etc.) and may have certain advantages and disadvantages in efficiency of collapse prediction.

Ground motion records often need to be scaled in increasing intensity to predict collapse, because of the small number of available motions with sufficient energy to collapse modern buildings. Recent research has shown that accurate collapse assessment depends on selection of ground motions whose spectral shape is representative of the motions likely to cause collapse (Haselton and Deierlein 2007; Baker and Cornell 2005). Spectral shape is important because most structures collapse under very rare (infrequent) ground motions and, especially in California, these rare ground motions have a distinctive spectral shape. Methods developed by the authors (Haselton and Deierlein 2007) show that ground motions can either (a) be selected to have the proper spectral shape or (b) results of collapse performance assessment can be modified to account for spectral shape. In California, not properly accounting for spectral shape may lead to a 20 to 60% change in the predicted collapse resistance of the structure.

Incremental Dynamic Analysis. Incremental dynamic analysis (IDA) is an important method for evaluating the collapse resistance of nonlinear simulation models (Vamvatsikos and Cornell 2002). In IDA, a building model is subjected to a suite of recorded or synthetic ground motion accelerograms. Each record is individually applied to the structure, scaled in increasing intensity, each time recording structural response, until collapse occurs. Provided that the analysis model accounts for critical component and system-level failure modes and robust solution algorithms are used to achieve convergence, structural collapse may be predicted from dynamic instability. Results of incremental dynamic analysis for an 8-story nonductile RC space frame, subjected to a suite of 44 ground motion records, are shown in Figure 3. Direct collapse simulation also reveals the possible collapse modes of the structure of interest; the 8-story nonductile RC frame commonly fails due to formation of a mechanism in the bottommost two stories. Depending on the structure, the complexity of the analysis model and computing power available, it may take between several hours and several days to conduct IDA for a single structure.

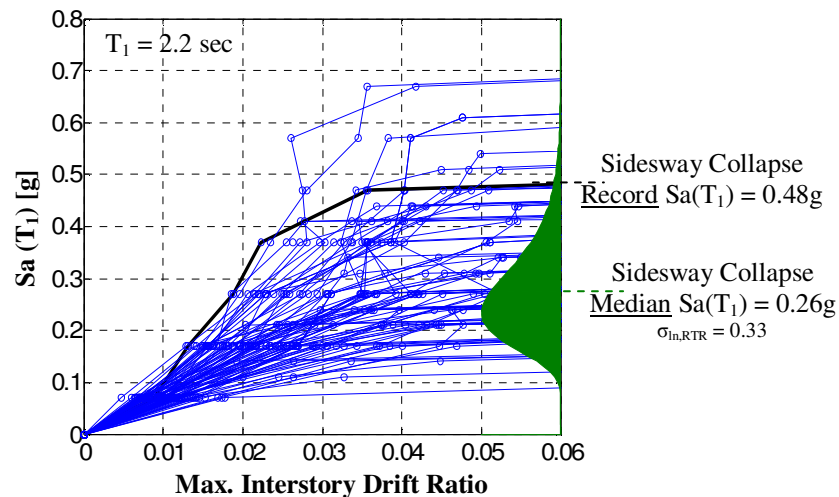


Figure 3. IDA results for an 8-story nonductile RC frame structure subjected to 44 earthquake records, including statistics on seismic collapse resistance.

The outcome of the assessment is a seismic *collapse fragility* function, shown in Figure 4, which predicts the probability of collapse as a function of the ground motion intensity for a particular structure. The mean and standard deviation of the collapse fragility are obtained from statistics on IDA results, as illustrated in Figure 3. Variation in collapse capacity (termed ‘record-to-record’ variability, $\sigma_{ln,RTR}$) occurs because of differences in frequency content and other ground motion characteristics.

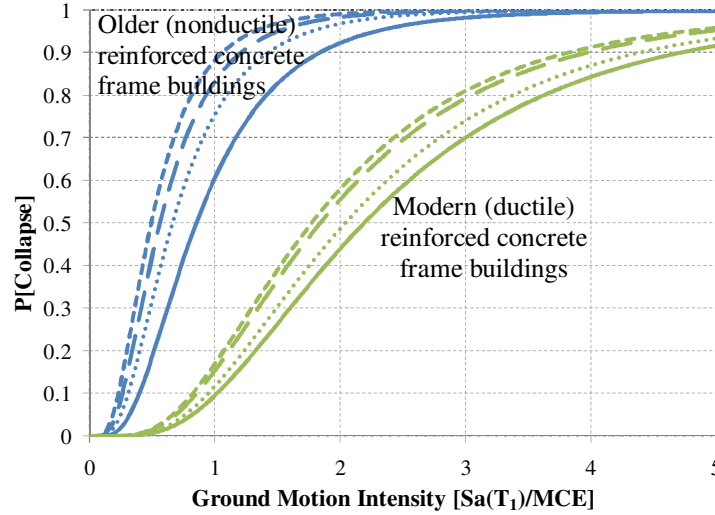


Figure 4. Predictions of seismic collapse risk for California RC frame buildings at a typical high seismic coastal California site (Haselton and Deierlein 2007; Liel and Deierlein 2008).²

Incorporating Uncertainties in Structural Modeling and Design. Due to the complexities in predicting ground motions and structural response in future earthquakes, comprehensive assessment of the risk of earthquake-induced requires explicit consideration of sources of uncertainty. The largest uncertainty lies in characterizing the earthquake ground motions. Uncertainties in ground motion intensity are represented by the site-specific hazard curve, and the additional uncertainties associated with frequency content and other attributes of the ground motion records are quantified in record-to-record variation. There are also uncertainties in simulating the structural response, relating to the extent to which the idealized analysis model accurately represents real behavior. A primary source of modeling uncertainty lies in definition of the analysis model parameters – specifically the strength, stiffness, deformation capacity, and energy dissipation characteristics of the building components. Recent research has shown that modeling uncertainties can have a significant impact on predictions of probability of collapse and other metrics (Liel et al. 2009) because of the large underlying uncertainty in prediction of parameters needed to model collapse. Simplified methods for incorporating modeling uncertainties in assessment of seismic collapse risk are discussed elsewhere and may increase the variability and shift the mean of the seismic collapse fragility.

² In Figure 4, the maximum considered earthquake (MCE) is assumed to be equal to the ground motion intensity that is exceeded with 2% likelihood every 50 years, $Sa_{2/50}(T_1)$. This approximation is valid at most sites that are not in the near-field region, including the site of interest.

Metrics for Seismic Collapse Risk. Seismic collapse assessment results in a collapse fragility curve, providing several possible metrics of seismic collapse risk for a particular building. The median collapse capacity is the ground motion intensity, $S_a(T_1)$ [g], corresponding to a 50% probability of collapse. Another metric is the probability that a structure will collapse when subjected to a ground motion of specified intensity. Although in concept conditional probabilities could be computed for any ground motion intensity, the probability of collapse associated with code-defined MCE is frequently reported. The mean annual frequency of collapse for each structure is obtained by integrating the collapse fragility function with the ground motion hazard curve.

Assessments of seismic collapse risk for buildings have yielded a number of interesting results. For example, Figure 4 predicts the probability of collapse as a function of ground motion intensity for two sets of California buildings: older nonductile RC frame buildings, representing existing (pre-1970) construction, and modern ductile RC frame buildings, representing today's code-conforming construction. As the figure shows, the probability of collapse is much higher for the existing concrete frame buildings than newer buildings; if we look at the conditional probability of collapse, given the occurrence of the MCE level earthquake at a typical high seismic site ($S_a(T_1)/MCE = 1$), the existing RC buildings are approximately eight times more likely to collapse (Liel and Deierlein 2008). These results may be used to facilitate development of provisions recommending retrofit of the more vulnerable nonductile RC frame buildings existing in California. In a separate study, Haselton and Deierlein (2007) showed that 12 and 20-story reinforced concrete moment frame structures designed according to the provisions of ASCE 7-05 have higher risks of earthquake-induced collapse than shorter buildings. These results, which were also included in the ATC-63 project report (ATC 2008b), led to a change minimum base shear requirements for taller buildings in a recently published supplement to ASCE 7-05, reverting to the requirements of ASCE 7-02.

Challenges and Opportunities in Seismic Collapse Assessment. Direct simulation of collapse is, of course, fraught with complexities related to ground motion selection, hysteretic modeling of critical failure modes and incorporation of modeling uncertainties. Despite the limitations of analytical methods, there is little empirical or experimental data on system-level collapse behavior. Now that some collapse simulations have sufficient resolution for comparative assessment, analytical collapse simulations are increasingly being utilized as a vehicle for evaluating and improving seismic design provisions (ATC 2008b; Krawinkler and Zareian 2007).

SEISMIC PERFORMANCE ASSESSMENT FOR HIGHWAY BRIDGES

As with buildings, there have been substantial efforts in recent years to apply performance-based earthquake engineering methods to assess the seismic performance of bridge and transportation structures. This section reviews several papers developing seismic fragility curves for bridge systems, in order to provide an overview of the topics and directions of recent research on seismic safety of bridge systems. Research on seismic performance assessment for highway bridges has made significant advancements in prediction of non-collapse limit states and damage (spalling, residual drifts, rebar buckling, etc.), repair costs and bridge closure. The

vision here is that the collapse prediction methods outlined earlier in this paper can be adapted for bridges to supplement current assessments, in order to develop comprehensive predictions of bridge seismic performance – ranging from response under small frequent earthquakes to large collapse-level response affecting seismic safety.

Similar to the collapse fragility curves described in the previous section, bridge seismic fragility predictions developed in past research describe the probability of exceeding a particular damage state as a function of ground motion intensity. Fragility curves may be generated for any level of damage, ranging typically from ‘slight’ (minor cracking and spalling) to ‘complete’ (where the structure is assumed to be close to collapse). Methods for predicting seismic performance for bridges have changed over time. Early fragility curves were often based on empirical data from past earthquakes; for example, Basoz et al. (1999) used information about bridge damage from the Northridge earthquake to develop fragility curves for typical California bridges. Other efforts used nonlinear static (pushover) analysis to develop fragility curves. This discussion focuses on fragility curves developed using nonlinear dynamic analysis to predict the likelihood of seismic-related bridge damage (Gardoni et al. 2002; Kunnath 2007; Mackie et al. 2008; Mackie and Stojadinovic 2007; Mackie and Stojadinovic 2001; Nielson and DesRoches 2007c; Nielson and DesRoches 2007a; Nielson and DesRoches 2007b; Choi et al. 2004; DesRoches et al. 2004). As with buildings, it has only recently become possible to simulate nonlinear behavior of bridge structures to highly damaged and collapse limit states.

Mackie et al. (2008; 2007; 2001) have evaluated the seismic performance of typical configurations of Caltrans construction, focusing on multispan cast-in-place box-girder bridges. These evaluations utilized 3-dimensional nonlinear models of bridge columns, abutments, deck and expansion joints in OpenSees to predict structural response of bridges when subjected to recorded ground motions. The structural analysis results were then used to compute the likelihood of three possible damage states occurring: column spalling, longitudinal bar buckling, or failure. Component fragility functions, e.g. reporting the probability of spalling as a function of the level of drift, were used to predict damage states. Since column damage is expected to dominate the seismic response of California highway bridges, these limit states are taken to represent bridge seismic performance. The column failure limit state is expected to represent incipient collapse. Damage predictions were also used to probabilistically predict the likelihood of exceeding \$X in repair costs; information on repair costs is very useful for planning financial preparedness for future earthquakes. A separate paper shows how these bridge fragility curves could be used to improve design of typical California highway bridges (Mackie and Stojadinovic 2007).

In another project, researchers conducted a comprehensive evaluation of the seismic performance of steel and concrete simply-supported and continuous multispan bridges in the central and eastern U.S. (Nielson and DesRoches 2007c; Nielson and DesRoches 2007a; Nielson and DesRoches 2007b; Choi et al. 2004; DesRoches et al. 2004). These studies, which examined nine classes of common three-span zero-skew bridges, used three-dimensional nonlinear models in OpenSees, subjected to synthetic ground motions representative of earthquakes in this region of

the U.S. Damage limit states for columns, abutments and bearings were identified during dynamic analysis from a set of component fragility functions. These component failure modes are combined (using the total theorem of probability and appropriate assumptions about correlations) to assess the likelihood of slight, moderate, extensive and complete damage in the bridge system. Figure 5 shows fragility curves obtained for the complete damage state for selected bridges. These results suggest that continuous-span bridges tend to be more vulnerable than their equivalent simply supported counterparts.

A number of other important studies have advanced bridge seismic performance and are mentioned only briefly here. Lee and Billington (2006) investigated the seismic response of highway bridges, specifically focusing on predicting (and reducing) residual drifts. Prediction of residual drifts is critical, because they can have great impact on the operability of a bridge after a seismic event. Kunnath (2007) coordinated an extensive performance-based assessment of the I-880 viaduct in Oakland by PEER researchers. Assessment of the viaduct, which was based on dynamic analysis of a nonlinear model including column fiber elements, soil-structure interaction and expansion joints, focused on prediction of tangential drift for estimation of column damage in the structure (particularly spalling and buckling of longitudinal reinforcement). The report also predicted the closure probability of this important transportation route on the basis of column damage. Gardoni et al. (2002) have developed probabilistic methods for predicting system level bridge fragilities on the basis of component fragility information.

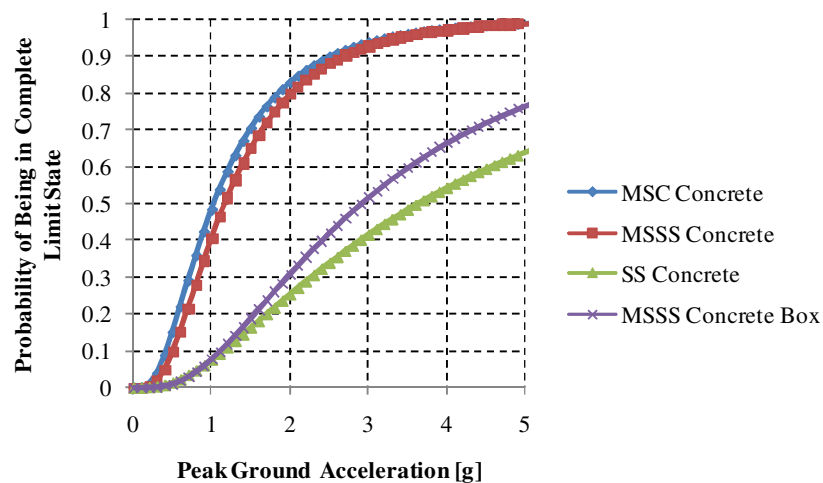


Figure 5. Selected fragility curves for the *complete* bridge limit state, from Nielson and DesRoches (2007a), where MSC is a multi-span continuous girder bridge, MSSS is a multispan simply supported girder bridge and SS is a simple span girder bridge.

As should be evident from the brief description of research related to seismic performance assessment of bridges here, much progress has been made in development of nonlinear simulation models for bridge structures, estimation of damage in bridge columns, expansion joints, abutments and other critical components, generation of seismic damage fragilities for different types of bridges, and prediction of bridge closure. These advancements are critical for improving the

seismic reliability of our transportation network and informing emergency response and mitigation plans.

DIRECT COLLAPSE ASSESSMENT OF BRIDGES

To date, research assessing seismic performance of bridges has not emphasized direct assessment of seismic collapse risks. Instead, the focus has been on predicting damage and losses; these limit states are critical in evaluation of relatively new highway networks because modern bridges, notably those designed by Caltrans, are conservatively designed and earthquake-induced collapse is expected to rare, even under very large ground motions. In addition, past research has rightly concentrated on evaluating bridge closure, recognizing the importance of minimizing disruption of transportation routes for post-earthquake emergency response and for movement of goods and services in our modern economy.

However, direct prediction of seismic collapse risk for bridges remains important, in order to characterize the complete range of seismic performance for bridge systems. Metrics of seismic collapse risk more effectively represent seismic safety than other component and system level limit states, providing a mechanism for explicitly considering the safety of drivers on or below highway bridges during the earthquake. These metrics could be used to improve new bridge design and assess existing bridges. Specific applications of assessment of seismic collapse risk for highway bridges include:

- Evaluation of new bridge design explicitly from a seismic safety perspective. Though Caltrans bridge designs are thought to be highly conservative, some bridge types, such as skewed bridges, may be more vulnerable than others, but these differences have not been directly quantified in terms of collapse risk.
- Analytical assessment of existing bridge structures to identify those highway bridges that are most vulnerable to earthquake-induced collapse. These bridges may be good candidates for retrofit or replacement. These assessments are critical because existing bridges make up a significant part of the bridge portfolio throughout the U.S. and many have inadequate seismic resistance.
- Provides a method for improving the collapse fragilities for bridge systems that are included in software such as HAZUS. This software is frequently used to evaluate the impact of a scenario earthquake on an identified urban area; updated fragilities better these assessments.

Recent research on seismic collapse risks of buildings and seismic performance assessment for bridges provides a solid foundation for evaluation of seismic collapse risks in bridges. It is envisioned that the procedure applied to evaluate risks of earthquake-induced collapse in buildings could be adapted for bridges, based on incremental dynamic analysis of nonlinear simulation models for archetype bridge structures. Research demonstrating the importance of ground motion spectral shape and incorporation of modeling uncertainties for assessment of collapse risk is directly relevant, and should be incorporated in assessment procedure for bridges. Much of the work in previous bridge seismic performance assessment related to development of archetype structures (Mackie and Stojadinovic 2001; Nielson and DesRoches 2007a), creation of nonlinear simulation models (Kunnath 2007; Mackie et al. 2008;

Choi et al. 2004), and quantification of ground motion intensity (Mackie et al. 2008; Padgett et al. 2007) can provide the groundwork for these assessments.

More than anything, efforts described in the first part of this paper evaluating the collapse risk of building structures have demonstrated the effectiveness and usefulness of predicting seismic collapse risks for use in decision-making related to seismic design and evaluation. As computational capabilities and simulation models for bridges and buildings continue to improve, predictions of seismic collapse risk will gain accuracy and importance.

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