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Development of Bridge Repair Estimate Models For Use In Bridge Fragility Curves

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ABSTRACT

Bridge seismic fragility curves are statistical functions that give a probability of exceeding a certain damage level as a function of a ground motion intensity measure (i.e. PGA, Sa). These curves are widely used in numerous applications that are of interest to the bridge engineering community. Such applications include vulnerability assessment, retrofit prioritization, and lifeline evaluation. Moreover, fragility curves are key components of the seismic risk assessment of transportation networks. Traditionally, fragility curves are based on 4 to 5 damage states (i.e. slight, moderate, extensive, complete), which are based primarily on physical descriptions of damage (i.e. column curvature, deck displacement, etc) of a structure. These physical damage descriptors may not provide the best estimate of the cost to repair a structure after an earthquake or the associated functionality and downtime. This study focuses on developing curves using damage states that are based on realistic repair cost and repair time estimates, which are developed for individual components of a bridge, and aggregated to determine the overall bridge repair costs and downtime. The paper discusses the repair model for determining the repair cost and time estimates for individual bridge components, and the use of these models in incorporating them into fragility curves.

Introduction

Bridge seismic fragility curves are statistical functions that give a probability of exceeding a certain damage level or state as a function of a ground motion intensity measure. The function can be written as $P[\, DS_i \mid PGA=y \,]$, where PGA (peak ground acceleration) is an example of a ground motion intensity measure, and DS_i is the damage state in question. Applications of fragility curves include aiding in emergency response optimization, design support for performance-based engineering, planning support for seismic events, and policy support. The current damage states used in most fragility curves refer to the state or condition of a bridge following an earthquake event. States such as "Moderate" or "Complete" damage are an indication of the capacity that may be left in the bridge or bridge component. There is a need, however, for an engineering official to estimate the time and cost needed to repair bridges after an earthquake. Creating fragility curves using cost-based or repair time-based damage levels will be beneficial in pre-disaster planning by giving officials an estimate of the costs and time needed to bring the bridge to its former operating level after an earthquake event. The ideas presented in this paper include qualifying the damage of bridge components through a visual survey, quantifying the damage in terms of time and costs to repair, and compiling this information as an

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accessible reference for pre-earthquake planners and post-earthquake inspectors. The new damage states, drawn from the compiled information, will be based on total repair cost or total downtime of a particular bridge after an earthquake event. This paper will outline the strategy for creating the new damage states and incorporating them into the fragility analysis of a bridge.

Existing Methods for Fragility Analysis

Past research has produced many fragility curves. Early fragility curves were based on expert opinion (ATC, 1985). In a literature review on the use of expert opinion in risk analysis, five basic principles were given that is meant to provide a consensus amongst the responses. The five principles are reproducibility of results, accountability of the sources of data, empirical control of an expert's assessments, neutrality of the expert's opinions to make sure they are consistent with the expert's actual views not swayed by any incentives, and finally, the principle of fairness employed to make sure all opinions are regarded equally (Ouchi, 2004). These types of judgmental fragility curves are not limited to any particular damage or structural types; however the reliability of the information gained is difficult to quantify (Jeong, 2007).

Empirical methods have been used to develop fragility curves in regions where extensive earthquake records are available, such as California and Japan (Nielson and DesRoches, 2007). Empirical curves are based on observed damage from past earthquakes. Shinozuka, et al, used empirical fragility curves in their analysis of Caltrans' bridges. Damage reports were used to establish the relationships between the damage states and the level of ground motion intensity. They used two-parameter lognormal distributions to develop the curves of the bridges which were broken up into several structural subsets, where each level subset was more homogeneous in content than the previous. Several methods were used to estimate the parameters, and the results compared well (Shinozuka, 2007b). These types of fragility curves tend to be the most realistic, but are very specific to a particular earthquake and structure and have limited applications (Jeong, 2007).

Analytical methods are used to develop curves for bridges in regions where earthquake history records are not available, such as the Central and Southeastern United States (Nielson, 2007). Analytical curves are developed using distributions simulated for an analysis of a structural model Jeong, et al., proposed a new kind of analytical fragility framework by characterizing a response database and responses by fundamental values of stiffness, strength and ductility. In this way, they were able to avoid excessive analysis needed with traditional analytical fragility curves. The results were shown to be comparable with more rigorous analysis. Analytical curves are limited by computation efforts and may be calibrated to increase the accuracy by available observational data (Jeong, 2007).

Hybrid fragility curves combine data from different sources. These can be used to obtain more reliable curves because of the variety of sources of information (Jeong, 2007). Kappos, et al, developed a hybrid model combining a statistical approach and an analytical approach. They used existing damage data available for certain ground motion intensities, and supplemented that data with results of an inelastic dynamic analysis of structural models. This method made it possible to construct a damage probability curve in areas where limited empirical data is available. The use of analytical models in combination with empirical data allowed the author to construct more appropriate cost-benefit analyses. The authors also calibrated their models against data from a past earthquake, with which the models were consistent (Kappos, 1998).

Exploring Past Damage States

The damage states used in fragility curves have traditionally been the following four levels: Slight, Moderate, Extensive, and Complete (Table 1) (Choi, 2004). The (N) damage level is usually not included in fragility analysis. These four categories apply to a particular component of the bridge being analyzed, such as the columns, footings, and abutments. Many fragility curves focus on the response of one component, such as the drift of a column, to indicate the state of a bridge after an earthquake event. However, the responses of other major bridge components are emerging as significant elements in determining the fragility of the entire bridge (Nielson and DesRoches, 2007; Padgett and DesRoches, 2008). Shinozuka, et al, discovered that the use of ductility capacity of columns as the definition of damage states resulted in an overly conservative estimate of the fragility curve of the bridge (Shinozuka, 2007a). While including the effects of other component states on the bridge functionality is important, finding equivalent measures of damage between components is a challenge. For example, extensive damage in a column of a bridge may lead to a longer bridge closure and more repair costs than extensive damage in a bearing. This paper seeks to highlight the importance of including other components in the overall state of the bridge efficiently, and why this repair model would be more effective in capturing the overall condition of a bridge following an earthquake.

Table 1: Damage States Commonly Used from Hazus (FEMA, 1997)

Damage States	Description
(N) – No Damage	No damage to a Bridge
(S) – Slight Damage	Minor cracking/spalling to abutment, cracks at hinges, minor spalling at column, or minor cracking to the deck
(M) – Moderate Damage	Moderate cracking and spalling at column, moderate settlement of approach, cracked shear keys or bent bolts at connection
(E) – Extensive Damage	Degraded column without collapse, some lost bearing support in connection, major settlement of approach
(C) - Complete Damage	Collapsed column, all bearing support lost in a connection, imminent deck collapse

To determine the damage level of a particular component, quantitative assessments may be in place for each component being inspected. For columns, it could be displacement or rotational ductility. For bearings, damage may be assessed by measuring the displacement of the bearing or deck from its original position. Often, the engineer must rely on his or her judgment to visually inspect the components and relate a damage level based on experience and the description above. Therefore, if a bridge were inspected by different engineers, the results of the inspection and corresponding damage states may vary. Unified damage states, even within a region of the country in which the bridge is located, would allow for more confidence in the use of the resulting fragility curves.

Aslani, et al, described a method of estimating economic losses due to damage to a component (Aslani, 2005). The approach involved defining component level damage states on the basis of specific repair actions due to observed damage. These damage states facilitate the estimation of economic loss with loss functions, which are probabilistic estimates of the cost to repair a component at a given damage state. What the proposed repair model attempts to do is, instead of Aslani's two step approach to find the economic losses due to component damage, create a one step approach.

Creating Updated Damage States with Repair Model

The repair model suggested in this paper is composed of major bridge components, including column, bearings, abutments, and foundations. The components are then separated by the types of damage possible, such as a ductile or brittle damage for the columns. For each type of damage within the bridge component there are four levels. Each level indicates progressively more damage than the last. For each level, a description of the visible damage is given and a few photos that display the corresponding damage. The figures used to indicate the level of damage were compiled from the Caltrans Report No. CA08-0284 (Sashl, 2008). This report is used by bridge engineers and inspectors to provide a uniform summary of damage and expected load carrying capacity for tagging bridges following an earthquake. The survey is to be filled out by several practicing engineers, preferably those with experience in earthquake damage inspection and repair. The data collected from this model gives the bridge carrying capacity after the earthquake event, the repair method for that level of damage, and approximate costs and times until the repair is completed. Below are sample repair models for a column with brittle damage and foundations with ductile damage (Fig. 1 and 2) and a figure showing the survey to be completed for each level of damage within the repair model (Fig. 3). The surveys completed by engineers are compiled and sorted by region and bridge type. The responses would then be used to create the new damage levels and subsequent fragility curves.

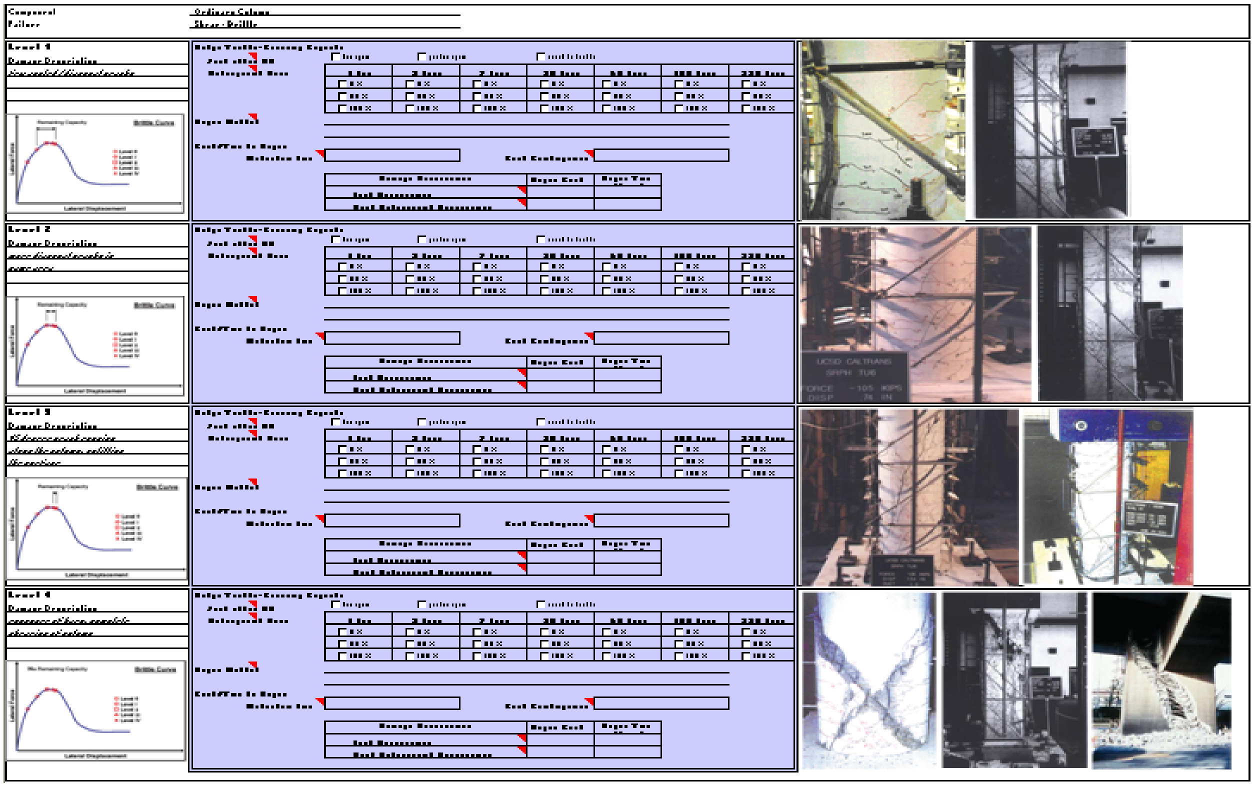


Figure 1: Component Survey for Column with Shear Damage

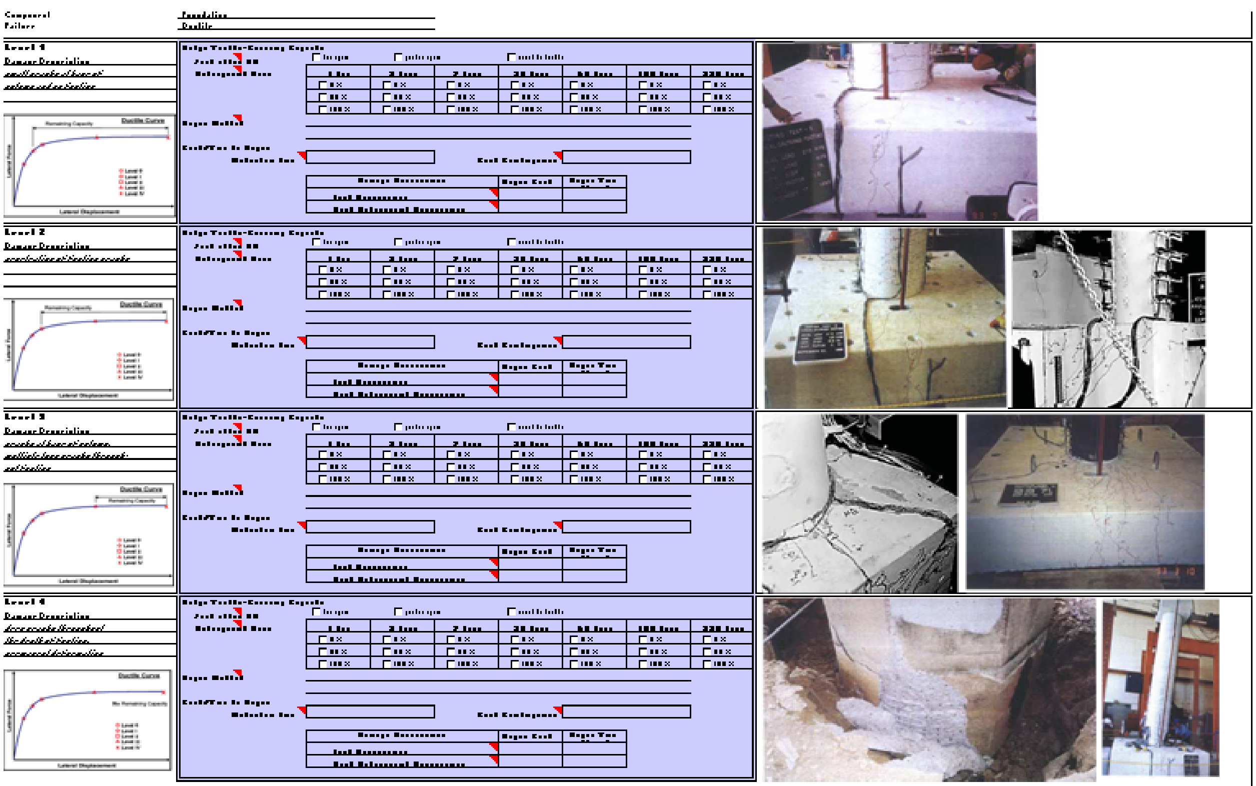
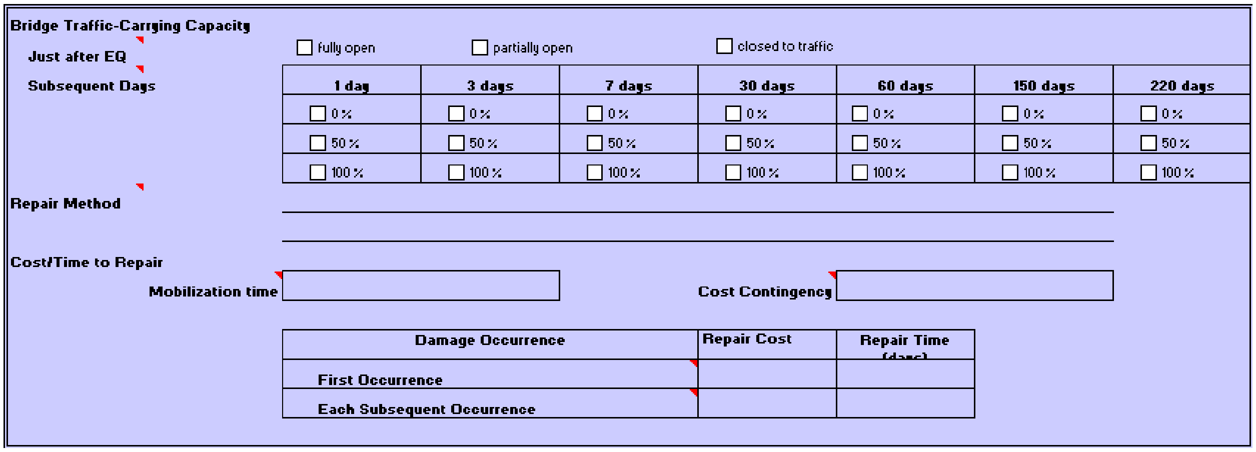


Figure 2: Component Survey for Foundation with Ductile Damage


Bridge Traffic-Carrying Capacity

Just after EQ: ☐ fully open ☐ partially open ☐ closed to traffic

Subsequent Days

1 day	3 days	7 days	30 days	60 days	150 days	220 days
☐ 0 %	☐ 0 %	☐ 0 %	☐ 0 %	☐ 0 %	☐ 0 %	☐ 0 %
☐ 50 %	☐ 50 %	☐ 50 %	☐ 50 %	☐ 50 %	☐ 50 %	☐ 50 %
☐ 100 %	☐ 100 %	☐ 100 %	☐ 100 %	☐ 100 %	☐ 100 %	☐ 100 %

Repair Method

Cost/Time to Repair

Mobilization time

Cost Contingency

Damage Occurrence	Repair Cost	Repair Time (days)
First Occurrence		
Each Subsequent Occurrence		

Figure 3: Repair Model Survey to be filled in by Engineer

There are several areas within the survey that is required for the bridge engineers to complete. First is the bridge carrying capacity estimate following an earthquake at the particular damage level. The initial traffic condition on the bridge immediately after the earthquake event needs to be estimated (Fully open, Partially Open, Closed to Traffic). Then, the capacity after the indicated days have passed (0%, 50% or 100% traffic carrying capacity at 1, 3, 7 days etc.) should be approximated. This includes the time needed to inspect and repair the component in question, not taking into account the condition of the remainder of the bridge.

The next area of interest in this survey is the repair method. Here, the engineer can write in the technique most commonly used to repair the type of damage indicated. The information from this section will be helpful as a reference for those inspecting the bridges. This information is also helpful in determining the cost associated with potential retrofits on a regional level, and will be the basis for any future cost-benefit analyses.

The final section is of the most important to this study, which requests the approximate mobilization time, cost contingency and repair cost and times for each occurrence of this level of damage. The mobilization time, a portion of the downtime of the bridge, is the time between the earthquake event and the start of repair. This includes inspection and design time if needed. The cost contingency accounts for the uncertainty in the approximated repair costs. The repair costs and time are given for the first occurrence of this type of damage, and for each subsequent occurrence of damage at the same bridge. Repair completion times make up the rest of the downtime of a bridge. Downtime is a key decision variable in PEER's performance assessment methodology. Having mobilization time, repair time and costs, and cost contingencies can lead to a more detailed estimation of indirect losses due to the damage of the bridge, if future work focuses on this aspect of loss estimation (Comerio, 2006).

The fragility of the bridge will be dependent on the responses of the component, but mostly on the extent of the damage to the bridge. For example, if a damage level is the repair costs totaling to or exceeding $50,000, then the fragility curve will give the probability that the cost to repair the bridge will exceed $50,000 given a ground motion intensity measure. How the cost of repair reaches this amount may depend on any combination of damage to the bridge components, and should reflect the overall condition of the bridge. The way the individual cost and repair times are combined to determine the total bridge repair time and cost will be determined in the future. Nielson and DesRoches (2007) give a methodology used to create a system fragility curves from individual component fragility curves. Probabilistic seismic demand models (PSDM) are created for each component based on the peak response of the component to a given ground motion. The estimate of the system fragility can be found using a joint PSDM (JPSDM), which is the joint demand on the components. This methodology could possibly be used to combine the component level responses and create the cost-based and time-based damage states.

Benefit of Fragility Curves with Updated Damage States

The fragility curves that result from using the new damage states will be beneficial in many ways. The fragility curves would be useful for engineers who want to reduce the seismic risk of structures by implementing mitigating techniques against earthquake damage into their designs (Abrams, 2002; Foltz, 2004). Since the damage level will be cost-based or repair time-based, these curves would be beneficial to stakeholders, such as city managers, state transportation officials and owners, to determine the level of risk they are willing to accept in the event of a specified earthquake event. A curve developed during the design phase of the bridge can give the official an indication of the economic risks, or consequences, of the design given an earthquake before the structure is built.

In retrofitting decisions, this curve would give a clear indication of the possible economic losses in the event of an earthquake. Combined with the knowledge of the seismic risk in a region and the associated loss estimation to a bridge in that region, officials can prioritize retrofitting efforts or seismic damage prevention efforts according to specified loss criteria (Foltz, 2004; Padgett, 2007).

In the event of an earthquake, engineering officials and emergency teams need to pinpoint locations of life-threatening damage almost immediately. Using a fragility curve created with new damage states, they can base their decisions on estimations of damage to the entire structure instead of single components. Emergency planning will be benefitted as well, as the cost to repair in the event of an earthquake can be estimated using the fragility curves (Foltz, 2004), and be used to budget accordingly.

The fragility curves that use the new damage states can have more specific applications. Because the damage states depend on the amount of damage to each single component, the curves can be more specific in some instances, such as pertaining to unique or special bridges. The practicing engineer using this repair model to create curves can determine acceptable damage levels for the bridge it applies to. For example, a state agency can have a stock fragility curve that applies to common bridge types in the states, and also create special curves for a signature bridge. The damage levels for the signature bridge will likely have higher repair costs or longer times than the general curves for common bridges.

Future Work

In order to implement these new states, data is needed from practicing engineers on their responses to damages incurred after an earthquake. Since many engineers who are not located on the west coast may not have experience in this type of assessment, responses from a variety of engineers are desired. The surveys described above would be sent out to many agencies, with the intention of receiving a diverse set of responses. Next, with these data on the proposed costs to repair and repair times, fragility curves would be developed for multiple bridge types. These fragility curves will correspond to some bridges already modeled in past research. By analyzing similar bridges to ones previously analyzed with old damage states, direct comparisons can be made with the results of other damage levels and the ones produced by the new damage states.

The question of how to combine the differing damage levels from each component is still unanswered. For example, to determine reasonable damage levels that accurately depict “slight” to “complete” damage to a bridge, many combinations of the component damage must be considered, and the resulting costs should be calculated. Also, it must be decided whether to perform a linear combination of repair costs from all components to determine the total repair cost, as in the approach by Aslani, or create some model of combination using appropriate weights (Aslani, 2005).

While Aslani gave a possible approach to finding economic losses due to repair costs for damaged components, there remains the possibility of creating damage states based on repair times. These component damage states would not likely be created for the bridge damage states by linear combination, as overlap in repair times is likely. So this matter will need further investigation.

Conclusions

In this paper, the topic of fragility curves and the methodologies used to create them were visited. This paper presented an alternative to traditional damage states which describe the condition of a bridge. The proposed damage states will be based on the cost to repair the bridge or downtime of the bridge after an earthquake event. These damage states can be formed after practicing engineers complete the repair models. Future work will include developing the methodology to combine individual component responses to create the system level damage states, and to use those results to create fragility curves for different classes of bridges.

References

Abrams, D., Elnashai, A.E., and Beavers, J.E., 2002. “A new engineering paradigm: consequence-based engineering,” Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, Urbana, IL (http://mae.ce.uiuc.edu).

Aslani, H. and Miranda, E., 2005. “Probabilistic Earthquake Loss Estimation and Loss Disaggregation in Buildings.” *Report No 157,* Dept of Civil and Environmental Engineering, Stanford University.

ATC (1985). “Earthquake Damage Evaluation Data for California.” *Report No. ATC-13*, Applied Technology Council.

Choi, E., Nielson, B., and DesRoches, R., 2004. “Seismic Fragility of Typical Bridges in Moderate Seismic Zones,” *Engineering Structures 26 (2), 187-199.*

Comerio, M., 2006. “Estimating Downtime in Loss Modeling”, *Earthquake Spectra 22 (2), 340-365.*

FEMA, 1997. *HAZUS 97: Technical Manual*. Federal Emergency Management Agency, Washington DC.

Foltz, R., 2004. “Estimating Seismic Damage and Repair Costs,” *The Citadel*. Texas A&M.

Jeong, S. and Elnashai, A., 2007. “Probabilistic Fragility Analysis Parameterized by Fundamental Response Quantities” *Engineering Structures 29, 1238-1251.*

Kappos, A.J., Stylianidis, K.C., and Pitilakis, K., 1998. “Development of Seismic Risk Scenarios Based on a Hybrid Method of Vulnerability Assessment”, *Natural Hazards 17.*

Nielson, Bryant, 2005. “Analytical Fragility Curves for Highway Bridges in Moderate Seismic Zones”, *PhD Thesis*, Georgia Institute of Technology.

Nielson, B., and DesRoches, R., 2007. “Seismic Fragility Methodology for Highway Bridges Using a Component Level Approach,” *Earthquake Engineering and Structural Dynamics, 36 (6), 823-839*.

Ouchi, F., 2004. “A Literature Review on the Use of Expert Opinion in Probabilistic Risk Analysis”, *World Bank Policy Research Working Paper 3201.*

Padgett, J., 2007. “Seismic Vulnerability Assessment Of Retrofitted Bridges Using Probabilistic Methods”, *Ph.D. Thesis*, Georgia Institute of Technology.

Padgett, J. E., DesRoches, R. 2008 “Methodology for the Development of Fragility Curves for Retrofitted Bridges”, *Earthquake Engineering and Structural Dynamics 37 (8), 1157-1174.*

Sahs1, S., Veletzos, M., Panagiutou, M., and Restrepo, J., 2008. “Visual Inspection and Capacity Assessment of Earthquake Damaged Reinforced Concrete Bridge Elements” *Final Report No. CA08-0284.* Dept of Structural Engineering, UC, San Diego, Caltrans.

Shinozuka, M., Banerjee, S., and Kim, S., 2007a. “Statistical and Mechanistic Fragility Analysis of Concrete Bridges.” *Technical Report MCEER-07-0015.*

Shinozuka, M., Banerjee, S., and Kim, S., 2007b. “Fragility Considerations in Highway Bridge Design.” *Technical Report MCEER-07-0023.*