

# Sensitivity of Seismic Response and Fragility to Parameter Uncertainty

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**Abstract:** As the use for regional seismic risk assessment increases, the need for reliable fragility curves for portfolios (or classes) of structures becomes more important. Fragility curves for portfolios of structures have the added complexity of having to deal with the uncertainty in geometric properties, along with the typical uncertainties such as material or component response parameters. Analysts are challenged with selecting a prudent level of uncertainty treatment while balancing the simulation and computational effort. In order to address this question, this study first evaluates the modeling parameters which significantly affect the seismic response of an example class of retrofitted bridges. Further, the relative importance of the uncertainty in these modeling parameters, gross geometries, and ground motions is assessed. The study reveals that savings in simulation and computational effort in fragility estimation may be achieved through a preliminary screening of modeling parameters. However, the propagation of these potentially variable parameters tends to be overshadowed by the uncertainty in the ground motion and base geometry of the structural class.

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## Introduction

Regional seismic risk assessments are gaining popularity for analyzing the potential losses and consequences of an earthquake event on a region. These assessments are essential for risk management, decision making on retrofit and mitigation strategies, and emergency planning and response. Structural performance evaluations form a critical foundation for seismic risk assessments, yet pose a challenge in terms of the large uncertainty, which may be associated with such an evaluation. Sources of uncertainty include those which affect both the structural capacity and demand, including the seismic forces, material properties, and geometry. For studies that attempt to reflect the vulnerability of general classes of structures, such as typical classes of buildings or bridges, the potential sources of uncertainty naturally compound. However, these types of fragilities for portfolios of structures are often necessary for regional seismic risk assessments (Ramamoorthy 2006). As a result, analysts are posed with the challenge of selecting an appropriate level of uncertainty treatment for typical classes of structures. This necessitates an assessment of which parameters not only significantly affect the seismic

response of the structural system, but ultimately influence the system vulnerability.

Researchers have attempted to assess the sensitivity of the seismic demand or estimated fragility to varying parameters in a range of structural systems including buildings (Kwon and Elnashai 2006; Wang and Foliente 2006; Song and Ellingwood 1999), gravity dams (Tekie and Ellingwood 2003), non-structural components (Zhu and Soong 1998; Chaudhuri and Hutchinson 2006), and bridges (Kunnath et al. 2006). However, few have considered the impact of taking into account uncertainty inherent to a portfolio of structures, which have the additional complexity of geometric uncertainties and structure-to-structure variation in other parameters. Analysts of the fragility of portfolios of structures have utilized a range of fidelity of uncertainty treatment, from considering only ground motion uncertainty (Karim and Yamazaki 2001) to statistically varying over a dozen parameters (Nielson and DesRoches 2007) in simulations used to estimate the seismic demand. Without knowledge of the sensitivity of the failure estimate to propagating various uncertainties it is difficult to know what level of uncertainty treatment is necessary to assess the fragility of these portfolios of structures. One may either be disregarding significant parameters which could lead to unreliable fragility estimates; or conversely may exhaust efforts unnecessarily on time-intensive and computationally expensive statistical sampling and simulation which has minimal influence on the resulting fragility estimates.

Seismic risk assessments for transportation networks lend themselves to the use of fragilities for typical classes of bridges. Information available in the National Bridge Inventory (FHWA 1995) offers limited detail on the structural parameters, yet provides sufficient information to classify bridges into general categories based on material and construction type. There have been a number of studies which have evaluated the sensitivity of the seismic response of various components in bridges (such as bearing or column demands) through simplistic or robustly designed experiments (Saiidi et al. 1996; Jangid 2004; Nielson and DesRoches 2006); however, there is still a lack of overall

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understanding of the significance of a number of parameters in general classes of retrofitted bridges. Moreover, the propagation of various sources of uncertainty and ultimate effect of parameter variation on the resulting fragility estimate requires additional assessment, as provided by this study. Such an assessment helps to address and identify what levels of modeling fidelity and uncertainty treatment are necessary for risk assessment of these classes of structures.

This study assesses the significance of a number of modeling parameters on the seismic response of critical components within a retrofitted bridge (columns, bearings, abutments) through a traditional blocked fractional factorial design. In this type of analytical experiment, an economical fraction of the treatment combinations of modeling parameters is used in order to glean adequate information to assess the significance of varying the parameters (Wu and Hamada 2000). The modeling parameters investigated include those related to material uncertainty, such as concrete and steel strength; component response, such as bearing or foundation stiffness; geometric uncertainty, such as the gap between the deck and abutment; and retrofit parameters, such as restrainer cable slack or shear key gap. Other considerations include the incident angle of the earthquake and the base geometry of the bridges, which refers to the combination of gross geometric properties including span length, column height, and deck width. The ultimate objective of the study is to assess the impact of careful statistical treatment of the significant parameters on the resulting failure probability estimates, in order to assess the relative importance of ground motion uncertainty, geometric uncertainty, and modeling parameter uncertainty on the fragility of classes of retrofitted bridges. This study is illustrated with one specific bridge type (multispan simply supported steel girder). However, the general results are applicable to other common bridge types and the methodology and approach is relevant to other structural systems.

### **Characteristics, Modeling, and Uncertainty in Bridge and Retrofit Parameters**

The class of bridges used as an example in this study is the multispan simply supported (MSSS) steel girder bridge, which is one of the most common bridge types in the central and southeastern United States. The composite slab-on-steel girder decks are usually supported by single or multicolumn bents with pile foundations, and steel fixed and expansion bearings typically support the girders. These bridge types differ from those found on the west coast, where most bridges consist of multiple frames with box girder decks. Subsequently, the sensitivity of the seismic response of these bridges under various retrofit strategies to parameter variation is not well understood. However, past studies have found that these nonseismically designed MSSS steel bridges are vulnerable to potential span unseating due to short seat widths, failure of brittle steel bearings, and damage to nonseismically detailed columns having limited ductility and low shear strength (DesRoches et al. 2004). To overcome such vulnerabilities, bridges can be retrofit using a number of different strategies. The retrofit measures considered in this study which address some of the deficiencies common to MSSS steel bridges include the use of seat extenders, steel restrainer cables, steel jacketing of columns, elastomeric isolation bearings (EB), and shear keys.

### **Analytical Modeling**

Although further details of the analytical modeling of the as-built and retrofitted MSSS steel girder bridge can be found elsewhere (Nielson and DesRoches 2006; Padgett 2007), the general approach is presented herein. Three-dimensional analytical models developed in *OpenSees* (McKenna and Fenves 2005) are used in time history analyses to simulate the seismic response of the retrofitted bridges. The composite steel girders and concrete deck are modeled with linear beam-column elements, as they are expected to remain elastic. However, the nonlinearities of other components are reflected in the model, such as the longitudinal and transverse behavior of the steel bearings (Mander et al. 1996), and the active, passive, and transverse response of the abutments using nonlinear inelastic springs. The columns and bent caps are represented with fiber models, foundations with linear rotational and translational springs, and pounding captured through a nonlinear contact element.

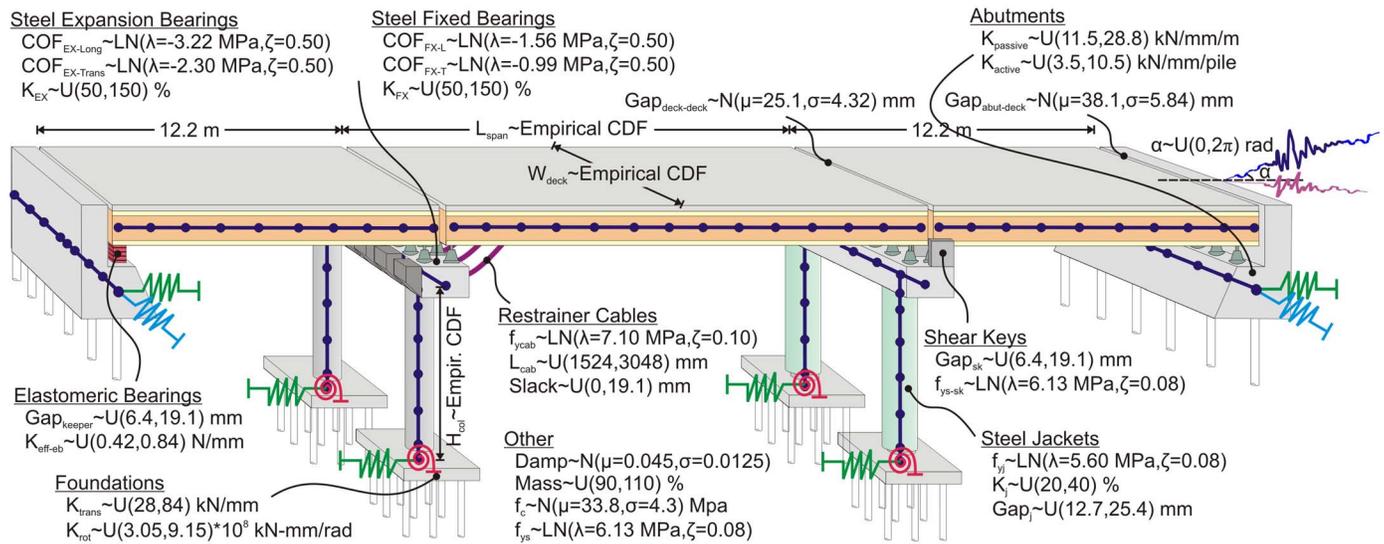
The retrofit models are also established with an emphasis on representing potential nonlinear behavior of the retrofitted component. The steel jackets are modeled by altering the column fiber models to depict the enhanced confinement as well as the observed slight increase in column stiffness due to jacketing. A coulomb friction model is used to reflect the response of the shear keys in the transverse direction with a gap before the shear key engages. The steel restrainer cables are modeled with nonlinear tension-only springs with a gap to represent the initial slack in the cable. Last, the elastomeric bearings are modeled with bilinear elements following Kelly's (1998) recommendations with inelastic springs for the transverse keeper plates.

### **Uncertainty Modeling**

A number of sources of uncertainty are present in the modeling and performance assessment of portfolios of retrofitted bridges. Sources of uncertainty affecting structural performance are often characterized as either aleatoric or epistemic in nature. Aleatoric uncertainty refers to that which is inherently random, or stems from the unpredictable nature of events, whereas epistemic uncertainty is that which is due to a lack of knowledge, and stems from incomplete data, ignorance, or modeling assumptions. Although the nature and sources of uncertainty are not always self-evident, many analytical modeling parameters can be attributed to a lack of knowledge of the actual bridge parameters (bearing stiffness, column height, etc.) and are epistemic in nature. Yet other parameters may stem from aleatoric uncertainty, including the inherent variability in material properties, such as the steel strength. The sources of uncertainty evaluated in this study can be generally classified as ground motion, gross geometry, and modeling parameter uncertainty. The potential variability in a number of the modeling parameters is indicated in Fig. 1. The sources are discussed further below.

### **Ground Motion**

The uncertainty associated with earthquake ground motions can range from uncertainty in the model used to develop the synthetic ground motions to that which is captured by the models and inherently variable in the suite of ground motions produced. An attempt can be made to address the former by considering a number of different ground motion models or suites in the seismic analysis, while the latter is explicitly captured in the ground motion suites utilized, which were developed by propagating uncertainties such as the source, path, and site characteristics. To



**Fig. 1.** Analytical model of retrofitted MSSS steel bridge indicating probabilistic models of uncertain parameters (N=normal; LN=lognormal; and U=uniform distribution)

address these needs, two suites of synthetic ground motions for the central and southeastern United States (CSUS) are used in this study, which were developed by Wen and Wu (2001) and Rix and Fernandez (2004). Another uncertain condition for structural performance assessment of bridges is the incident angle of the earthquake, and is also considered as a potentially variable parameter.

### Gross Geometry

Across classes of bridges, the geometric configurations can differ from bridge to bridge. Although all of the retrofitted bridges addressed by this study are nonskew three-span bridges, the span length, deck width, and column height may differ. Eight different base geometries for multispan simply supported steel girder bridges common to the CSUS have been identified in a past study by Nielson and DesRoches (2006), which used a Latin hypercube sampling technique and empirical distributions of bridge parameters to develop the combinations of geometric configurations. These geometries can be found in Table 1, with end spans of 12.2 m.

### Modeling Parameters

There are a number of additional analytical modeling parameters which are potentially variable in portfolios of retrofitted bridges. These parameters may be attributed to material strength, such as

the strength of concrete or yield strength of steel, which are the uncertain parameters that are often considered in vulnerability assessments. Other modeling parameters define the response of the bridge components, such as the stiffness of the bearings, coefficient of friction in the bearings, or stiffness of the foundations. Another group of uncertain modeling parameters can be attributed to the geometry of the bridges yet may be treated on a less macroscale level than the gross geometric properties such as the span length and column height. This includes such parameters as the gap between the decks, or between the bridge deck and abutment. Each retrofit measure has a number of potentially variable parameters associated with it due to uncertainty in the retrofit design or realization of the material properties or component response parameters. As an example, for a bridge retrofit with restrainer cables, there is uncertainty in the yield strength of the restrainers, slack in the cables, and length of the cables.

Nielson and DesRoches (2006) have identified likely ranges in the realized values for 14 modeling parameters associated with the as-built MSSS steel girder bridges. These parameters along with ten sources of modeling uncertainty attributed to the retrofits themselves are also assessed. The probabilistic models for these parameters are indicated on Fig. 1.

### Sensitivity Study with Example Bridge Class

Because there are a number of uncertain modeling parameters, a sensitivity study using analysis of variance is performed to assess which modeling parameters significantly affect component responses in each type of retrofitted bridge. The retrofitted multi-span simply supported steel girder bridge is used as an example for the study. Identified significant parameters will later be tested to evaluate the impact of propagating these sources of uncertainty through the fragility assessment. The responses considered in the study include the longitudinal and transverse deformations of the fixed and expansion bearings, the curvature ductility demands on the columns, and the passive, active, and transverse deformations of the abutments. The study performs a hypothesis test of the significance of varying the modeling parameters over their range

**Table 1.** MSSS Steel Girder Bridge Samples Adapted from Nielson and DesRoches (2006) Reflecting the Gross Geometric Uncertainty, or Variation in Base Bridge Configuration

Bridge	Center span length (m)	Deck width (m)	Column height (m)
1	18.30	9.53	5.10
2	20.40	9.53	3.62
3	15.50	9.53	5.95
4	13.70	9.53	4.02
5	25.60	20.96	3.54
6	7.30	9.53	3.90
7	8.80	9.53	4.26
8	10.40	15.25	6.62

**Table 2.** Parameters Associated with Each Retrofit Measure Considered in Sensitivity Study

Retrofit measure	Modeling parameter	Lower level	Upper level	Units
Restrainer cables	Yield strength of cable	149.5	207.5	MPa
	Slack in restrainer cable	0	19.1	mm
	Restrainer cable length	1524	3048	mm
Elastomeric bearings	EB effective stiffness	16.5	33.1	MPa
	Gap to keeper plate	6.4	19.1	mm
Steel jackets	Yield strength of jacket	237.9	307.5	MPa
	Gap between column and jacket	12.7	25.4	mm
	Stiffness increase due to jacket	20	40	%
Shear keys	Shear key reinf. steel strength	438.5	555.7	MPa
	Gap to shear key	6.4	19.1	mm

of potential realizations for each of the eight critical bridge responses.

### Experimental Design

A two-level fractional factorial design is used for the experiment, where the design pattern is generated with the aid of the statistical analysis program *JMP* (SAS 2004). This experimental design capitalizes on reducing the number of simulations from a full combination of modeling parameter levels, or from varying single factors at a time, in order to achieve a more economical design where the significance of each parameter can be statistically analyzed. This requires 32 runs with various combinations of high and low levels (treatments) of the bridge and retrofit parameters (factors). The upper and lower levels for the 14 modeling parameters identified by Nielson and DesRoches (2006) can be found elsewhere, whereas the ten parameter levels evaluated associated with the different retrofit measures are listed in Table 2. The high and low levels are set to encompass a reasonable range that the random variable may assume based on its probabilistic model.

The gross geometric parameters are accounted for by the use of a blocking scheme in which eight different bridge geometries are treated as separate blocks in the experiment. Additionally, the experiment is replicated two times using a total of three different earthquake time histories, resulting in 96 simulations for each retrofit type. Thus, we are trying to reduce the impact of a single ground motion's characteristics such as peak ground acceleration, frequency content, or strong motion duration on the response. The records used in this sensitivity study are synthetic ground motion records that were developed for Memphis, Tenn. by Rix and Fernandez (2004). The loading direction is also considered a potentially variable parameter, and the sensitivity study evaluates if bridge response is significantly impacted by loading the bridge in the longitudinal or transverse direction.

A run of the experiment, or single simulation, is defined as performing a nonlinear time history analysis in *OpenSees* (McKenna and Fenves 2005) of the bridge sample generated with the above specified parameter levels (treatments) for a defined input ground motion. The eight different peak component responses are monitored in each simulation in order to facilitate statistical analysis of the importance of each modeling parameter.

### Results of Sensitivity Study

An analysis of variance (ANOVA) is performed to evaluate the sensitivity of each component response to variation in the modeling parameters. Through this analysis of variance, a null hypothesis is tested which states that the coefficient of regression for

the multiple linear regression model of our experiment is zero (or the effect of varying the parameter is insignificant). In this assessment *p-values* are computed in order to interpret the results of the hypothesis test. The formulation for calculation of ANOVA tables including *p-values* can be found in most statistical analysis texts (Hines et al. 2003). However, smaller *p-values* indicate more evidence that the null hypothesis should be rejected and that the effect is indeed significant. For this study, parameters with a *p-value* less than a cutoff of  $\alpha=0.05$  are considered significant.

An example of one of the tables of *p-values* calculated as a part of the ANOVA for the MSSS steel girder bridge retrofit with EB is show in Table 3. This is the simplest experiment because it includes the least amount of modeling parameters and component response quantities of any of the retrofitted bridges, as all of the parameters and responses associated with the existing steel fixed and expansion bearings are no longer relevant. *p-values* indicative of a significant parameter are highlighted in Table 3. The most important parameters for this bridge, which affect at least three response quantities, are indicated in the Table. As expected, the loading direction is very significant, along with three additional modeling parameters: effective stiffness of the elastomeric bearing, rotational stiffness of the foundation, and the gap between the keeper plate and elastomeric bearing. The ANOVA also permits assessment of the impact of blocking on the response and reveals that the blocks have a significant effect. Thus, the potential variation in column height, span length, and deck width which yield different base bridge geometries has a statistically significant impact on the seismic response.

The sensitivity study reveals that for each of the other types of retrofits not shown (restrainer cables, steel jackets, shear keys) the loading direction has a significant impact on nearly every critical component response evaluated in the experiment, as does the blocking. In addition to these two intuitive parameters, several modeling parameters associated with both the bridge and retrofit measures also notably impact at least three responses. These parameters are listed in Table 4 for each retrofit measure. With the exception of the shear keys, every retrofitted bridge was sensitive to at least one modeling parameter that is attributed to the response of the retrofitted component. The variation in three modeling parameters (in addition to the loading direction and blocking) is found to be significant for at least three bridge component responses in the MSSS steel girder bridge retrofit with restrainer cables, steel jackets, and elastomeric bearings; and four modeling parameters for the shear key retrofit. Although these results indicate which uncertain parameters affect the seismic response of the retrofitted bridge, the propagation of these sources of uncertainty and influence on the fragility estimates are yet to be determined.

**Table 3.** *p*-values from ANOVA of MSSS Steel Bridge Retrofit with Elastomeric Bearings (EB)

Parameter	<i>p</i> -value					
	Abutment active	Abutment passive	Abutment trans	Column ductility	EB long	EB trans
Loading direction <sup>a</sup>	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>	0.878
<b>EB stiffness<sup>a</sup></b>	<i>0.000</i>	0.464	<i>0.014</i>	0.330	<i>0.000</i>	<i>0.000</i>
Foundation rotational stiffness <sup>a</sup>	0.264	0.952	0.012	<i>0.035</i>	<i>0.006</i>	<i>0.000</i>
<b>Keeper gap<sup>a</sup></b>	<i>0.006</i>	0.378	0.866	0.675	<i>0.000</i>	<i>0.000</i>
Abutment active stiffness	<i>0.000</i>	0.667	<i>0.000</i>	0.798	0.986	0.645
Hinge gap (deck-deck)	<i>0.028</i>	0.115	0.088	0.322	0.534	<i>0.000</i>
Concrete strength	0.937	0.681	0.303	0.120	0.707	<i>0.000</i>
Steel strength	0.670	0.772	0.560	<i>0.000</i>	0.663	0.110
Damping ratio	0.353	0.567	0.268	<i>0.000</i>	0.246	0.969
Mass	0.426	0.986	0.107	0.221	0.179	<i>0.000</i>
Abutment passive stiffness	0.753	<i>0.036</i>	0.286	0.268	0.326	0.110
Abutment-deck gap	0.840	0.426	0.253	0.772	0.499	0.170
Foundation horizontal stiffness	0.590	0.766	0.568	0.820	0.561	0.645
Block (base bridge geometry) <sup>a</sup>	<i>0.000</i>	<i>0.007</i>	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>	<i>0.000</i>

Note: Italics indicates a significant parameter (*p*-value < α=0.05). Boldface parameters are associated with the retrofit measure of interest.

<sup>a</sup>Identified as significantly affecting at least three component responses, and are termed the “most important” modeling parameters.

Their influence on the seismic fragility curves for the different types retrofitted bridges will be assessed in the next section.

## Fragility Analysis

### Analytical Fragility Curve Development

The goal of this paper is to assess the impact of parameter uncertainty on the fragility estimates for retrofitted bridges, rather than the methodology for the development of the fragility curves themselves. High level detail of the general analytical approach for developing the fragility curves for classes of retrofitted bridges is highlighted to provide context to the results, however further details of the methodology can be found in Nielson (2005) and Padgett (2007).

The fragility, or vulnerability, of a bridge represents the potential seismic performance of the system and reflects the uncertainty in the ability of the system to withstand a specified event. The fragility may simply be expressed as the conditional probability of the seismic demand exceeding the seismic capacity conditioned upon the ground motion intensity. This probability is often modeled with a lognormal probability distribution, and when the demand and capacity are both assumed to follow a lognormal

distribution, a closed form solution for the fragility may be presented as

$$\text{fragility} = \Phi \left[ \frac{\ln(S_d/S_c)}{\sqrt{\beta_{d|IM}^2 + \beta_c^2}} \right] \quad (1)$$

where  $\Phi[\bullet]$ =standard normal probability integral;  $S_c$ =median value of the structural capacity (or the limit state);  $\beta_c$ =its associated logarithmic standard deviation of structural capacity;  $S_d$ =median value of seismic demand; and  $\beta_{d|IM}$ =associated logarithmic standard deviation for the demand. These parameters must be estimated in the development of the fragility curves.

A nonlinear time history approach is taken to develop the fragility curves for this study, following the general methodology outlined by Nielson and DesRoches (2007) for as-built bridges common to the CSUS. Each permutation of the analytical bridge model is paired with a representative ground motion and nonlinear time history analysis is performed to monitor the peak component responses of the retrofitted bridge. The seismic demand placed on various critical components within the bridge (bearings, abutments, columns) is estimated through the establishment of probabilistic seismic demand models. Following the work by Cornell et al. (2002), this relationship is assumed to follow a

**Table 4.** Most Significant Parameters for Each Type of Retrofitted Bridge

Restrainer cable	Steel jacket	Elastomeric bearing	Shear key
Blocking	Blocking	Blocking	Blocking
Loading direction	Loading direction	Loading direction	Loading direction
Abut active stiffness	Abut active stiffness	EB stiffness	Damping ratio
Restrainer cable length	Damping ratio	Fnd rotational stiffness	Abut active stiffness
Damping ratio	Steel jacket stiffness	Keeper gap	Mass
			Hinge gap (deck-deck)

Note: Fnd=foundation and Abut=abutment.

power form allowing linear regression to be performed as shown in

$$\ln(S_d) = \ln(a) + b \ln(IM) \quad (2)$$

where  $S_d$ =median value of seismic demand; IM=intensity of the ground motion;  $a$  and  $b$ =unknown regression coefficients. The dispersion is also estimated through regression analysis.

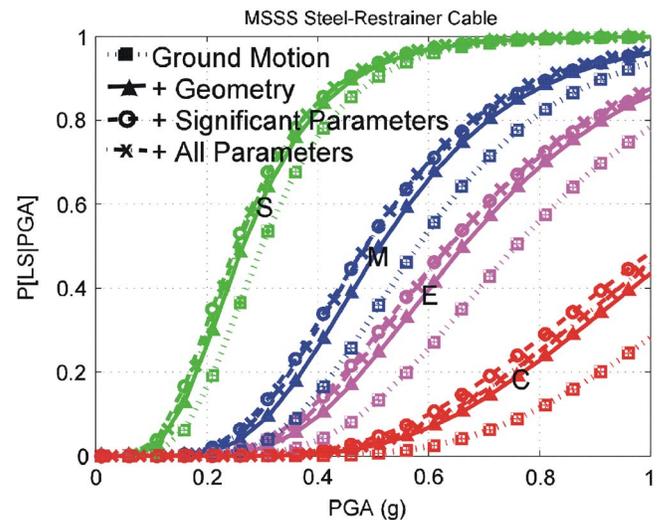
The seismic demand placed on each component is assessed against the capacity, or limit states, which are modeled by lognormal distributions. The capacity estimates presented in Nielson (2005) for the as-built components and Padgett and DesRoches (2007) for the retrofitted component are used in this study to assess the probability of meeting or exceeding slight, moderate, extensive, and complete damage. Using both the demand and limit state models, the fragility curves for each bridge component (bearing, abutment, and column) are generated using Eq. (1). The component fragilities are then combined to assess the overall bridge system fragility.

### Sensitivity of Fragility Curves

The parametric study presented reveals that the seismic response of various components in the retrofitted bridges are sensitive to a number of different modeling parameters, and the most significant parameters for each type of retrofitted bridges have been identified. The study also reveals the importance of considering the potential variation in loading direction and in the base geometries for portfolio analysis of retrofitted bridges (examined through a blocking analysis). The influence of carefully treating these different sources of uncertainty on the resulting fragility curves developed using the above outlined approach are assessed, by incrementally increasing the level of uncertainty treatment. Four sets of fragility curves, with different levels of uncertainty are considered as follows: (1) only the uncertainty in the ground motion; (2) uncertainty in the ground motion and gross geometry; (3) uncertainty in the ground motion, geometry, and most important modeling parameters identified in the sensitivity study; and (4) considering all of the identified potential sources of uncertainty.

The ground motion uncertainty captured and modeled by the fragility includes epistemic uncertainty in different ground motion modeling approaches by including suites of synthetic ground motions developed using the approaches of Wen and Wu (2001) and Rix and Fernandez (2004). Additionally, these researchers produced the ground motion suites with an effort to capture various sources of uncertainty in the source, path, and site characteristics which are then propagated through the fragility analysis. The ground motion uncertainty reflected in the fragilities also includes the unknown incident angle of the earthquake. The fragility curves developed considering only ground motion uncertainty assume a single base bridge geometry (Bridge 4 in the Table 1), and all other potentially uncertain modeling parameters previously discussed, such as the bearing stiffness, concrete strength, etc. are set to their median value. In addition to the ground motion uncertainty, the next level of uncertainty treatment evaluated for fragility estimation considers the potential variation in base bridge geometry which is inherent to an assessment of portfolios of retrofitted bridges. The eight base bridge geometries previously discussed and listed in Table 1 are used in this simulation.

The other two sets of fragility estimates present in Fig. 2 also include uncertainties due to the modeling parameters discussed previously in the sensitivity study, such as steel strength, bearing stiffness, etc. The base bridges are augmented using the Latin Hypercube technique to generate nominally identical but statisti-



**Fig. 2.** Comparison of fragility estimates with different levels of uncertainty treatment in the MSSS steel girder bridge with restrainer cables. S, M, E, and C indicate slight, moderate, extensive, and complete damage, respectively.

cally different bridges samples with a range of randomly generated modeling parameters. These sets of simulated bridge models are then used to analytically develop the fragility curves as outlined earlier. The set of fragility curves named “+ Significant Parameters” includes the variation only in the modeling parameters identified in Table 4 as the most significant parameters in the sensitivity study, in addition to the ground motion and gross geometric uncertainty. The fragility curves corresponding to “+ All Parameters” are generated with all potentially uncertain modeling parameters as random variables, as well as ground motion and gross geometric uncertainties. A total of 12–16 parameters are varied in these analyses, depending on the retrofit measure. These fragility curves represent the highest level of uncertainty treatment addressed in the study, and will be used as a basis of comparison for the other cases.

Assessment of the fragility estimates for the MSSS steel bridge retrofit with restrainers (Fig. 2) reveals that the fragilities developed considering the variation only in those modeling parameters identified as most important in the sensitivity study are nearly the same as those considering all potentially variable modeling parameters. The median values differ by only 0.4–2.6%. This is intuitive, as we have only varied those which significantly affect the seismic response of the critical components and thus impact the system vulnerability. These results reveal that we can save time and effort in simulating bridge models for the probabilistic seismic demand analysis by considering the variability only in those significant parameters identified in the sensitivity study.

It is interesting to note that there is relatively little difference between these fragilities and those developed considering only the uncertainty in the ground motion and base bridge geometry. Compared to the bridge considering all variable parameters, there is a 4.4–5.6% increase in the median values and a 1.6–6.6% decrease in the dispersion. In general, the uncertainty in the significant modeling parameters does not have a large effect on the fragility estimates, and the inclusion of only ground motion and geometric uncertainties may be adequate. It is evident from Fig. 2, however, that there is a notable difference in the fragilities when the variation in gross geometric properties is neglected and only ground motion uncertainty is considered. The median values

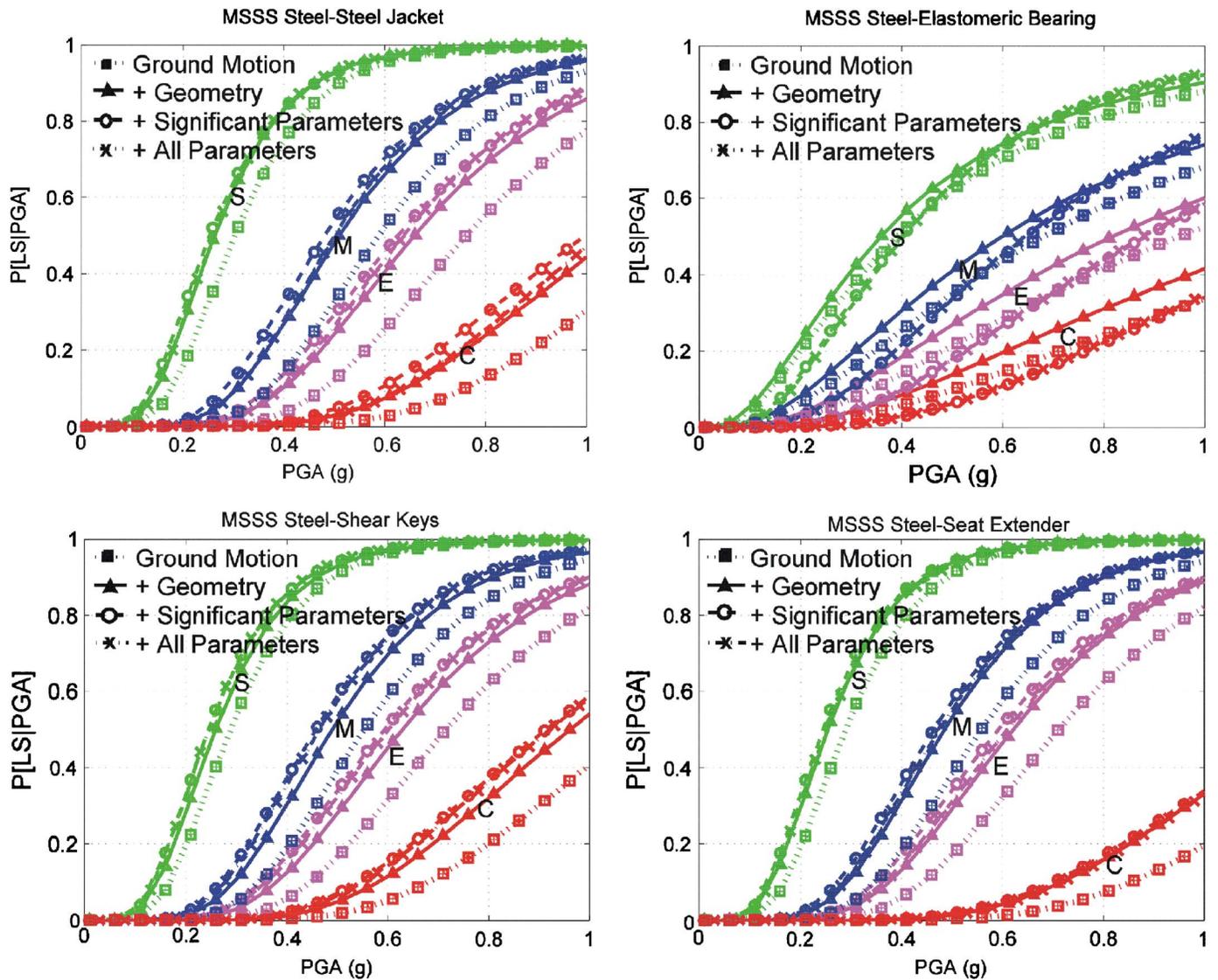


Fig. 3. Curves comparing the retrofitted bridge fragilities developed under increasing levels of uncertainty treatment

are 19.1–20.9% higher and dispersions 5.0–13.0% lower compared to the estimates with the highest level of uncertainty treatment. Without including the gross geometric variation in typical three-span steel girder bridges, the fragility for this portfolio may have been considerably underestimated, particularly at the higher damage states. Similar results were observed for the other retrofit measures, as shown in Fig. 3.

In general, the uncertainty in the ground motion and gross geometry overshadows the contribution of other sources of uncertainty attributed to the bridge modeling itself. These findings underscore the importance of carefully characterizing the range in base geometric configurations in developing fragility estimates for portfolios of structures, as well as the significant contribution of ground motion uncertainty that stems from the unknown incident angle of the earthquake, the random nature of ground motion, and the ground motion models (or synthetic suites) themselves which are used in the analysis.

The impact of increasing the level of uncertainty treatment in the development of fragility curves for the MSSS steel bridge retrofit with other measures is similar to the findings presented above for the restrainer retrofit, as depicted in Fig. 3. The difference in the fragility estimates with the other retrofits and the

as-built bridge were of a similar magnitude, and reveal the significance of incorporating not only ground motion uncertainty but also variation in base geometry. Additionally they show the similarity between the fragilities considering all parameters as variable and only those identified in the sensitivity study. Last, they indicate that incorporating the uncertainty in these modeling parameters often has little effect on the resulting median value of the fragility estimate. Slight differences in the dispersion are observed however, which could be important when convolving with the seismic hazard. The only exception is the elastomeric bearing retrofit. Although including only the significant parameters relative to the fragilities with all variable parameters still yields little difference, assuming the median value for all parameters leads to a greater difference in the estimated lognormal parameters than observed in the other retrofitted bridges: 4.4–9.8% difference in the median values and 25.6–32.8% difference in the dispersion.

Although this approach and the findings are presented for one class of bridges, the multispan simply supported steel girder bridge, assessment of other bridge classes yields similar results. Further details can be found in Padgett (2007).

## Conclusions

A range of potential sources of uncertainty associated with a seismic performance assessment of portfolio structures are identified and evaluated in this paper, using retrofitted MSSS steel girder bridges as a case study. The sensitivity study presented utilizes design of experiments principles to identify which modeling parameters significantly impact the seismic response of a number of different component responses in retrofitted bridges. The results of the study provide insight on the potentially uncertain modeling parameters that most significantly affect the seismic response of the retrofitted systems, which to date has not been thoroughly assessed. In addition to loading direction and blocking scheme (gross geometry), the most important parameters include those associated with the bridge itself (abutment stiffness, damping ratio, mass) as well as parameters associated with each retrofit measure (restrainer length, elastomeric bearing stiffness, steel jacket stiffness).

The findings of this sensitivity study are extended to evaluate which sources of uncertainty actually have a significant effect on the failure estimates and fragility curves for these portfolios of structures. The relative importance of sources of uncertainty with regard to ground motion, geometry, and modeling parameters is evaluated in a comparative assessment of fragility curves developed under increasing levels of uncertainty treatment. Fragility curves developed considering only those parameters identified in the sensitivity study as important are nearly identical to those developed with all potential sources treated as variables. This indicates that savings in simulation and computational effort may be achieved through a preliminary screening of parameters. However, this does not minimize the importance of carefully characterizing the potential range of modeling parameters in order to assign an assumed median value to these otherwise random variables.

The fragility is found to be particularly sensitive to the propagation of uncertainty in the base geometry (span length, column height, deck width) which is inherent to vulnerability assessments for structural portfolios. Considerable differences exist in the estimated parameters which characterize the seismic fragility, or the median and dispersion of the lognormal distribution, depending on whether or not gross geometric uncertainty is captured. It is observed that for this class of retrofitted bridges, considering only one "typical" bridge configuration coupled with ground motion uncertainty could lead to an unconservative estimate of the seismic fragility relative to the fragilities developed using a set of eight base bridge configurations under uncertain earthquake loading. Therefore, the potential variation in both the ground motion and base geometry are critical considerations for developing seismic fragility curves for these classes of structures. Moreover, these sources of uncertainty tend to overshadow those associated with modeling parameter variation, such as the damping ratio, elastomeric bearing stiffness, and length of restrainer cables. Careful definition of these modeling parameters could allow for deterministic treatment of a number of parameters whose variation has little effect on the overall fragility estimate. Efforts may be better spent in characterizing gross geometric configurations of the structure and addressing a number of factors which contribute to the ground motion uncertainty, such as loading direction, ground motion model, among others, and how to capture and propagate these sources through the fragility analysis. A word of caution is extended, however, that probabilistic treatment of the most significant modeling parameters identified in preliminary

screening can be critical for adequately accounting for the dispersion in the fragility estimate.

The study presented in this paper uses retrofitted bridges as a case study of portfolio structures to evaluate the sensitivity of the seismic response and fragility to parameter uncertainty, and highlights one class of bridges under a range of retrofit strategies. The results and conclusions, however, have been found to be valid across a number of different classes of retrofitted bridges, and should be valid for as-built bridges. Moreover, the problem of identifying an appropriate level of modeling fidelity and uncertainty treatment is a common theme in risk assessment of structural portfolios, and the approach presented is applicable to a range of structural systems. Such findings help maximize the return on efforts targeted at developing reliable fragility curves for classes of structures for use in regional seismic risk assessments.

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