Sensitivity Study of Design Parameters Used to Develop Bridge Specific Fragility Curves

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SUMMARY:
Bridges are essential lifelines for transportation networks during and after an earthquake event, providing routes for emergency response and evacuations. For this reason, bridge fragility modeling has been a major focus in earthquake research, as fragility analysis aids in the post-event determination of possible damage of bridges as well as in pre-event mitigation planning. While fragility analysis had been used for those purposes, this paper explores the use as a design aid. A bridge specific fragility methodology can be developed that takes into account certain design aspects of a bridge design in order to provide fragility curves particular to a bridge design. In order to support this fragility method, appropriate design parameters must be identified that most affect the response of a bridge, and will describe the fragility of a specific bridge given a set of these parameters. This paper conducts a sensitivity study to test which design parameters have a significant impact on bridge response and should therefore be considered as predictive variables in bridge specific fragility analysis used in the design process.

Keywords: fragility analysis, probabilistic seismic analysis, bridge design, sensitivity study

1. INTRODUCTION

Bridge seismic fragility curves are statistical functions that give the probability of exceeding a certain damage level or damage state as a function of a ground motion intensity measure. The fragility function can be written as $P[DS_i \mid IM=y]$, where IM=y stands for a ground motion intensity measure taking a particular value, and DS_i is the exceedance of the damage state in question. Fragility curves are tools used to assess and mitigate the effects of earthquake ground motions on structures, and their popularity was motivated by the development of earthquake loss models (Calvi, et al. 2006).

California is a state with a high seismic hazard. Because it has experienced many devastating earthquakes and the aftermath of those events, California has been in the forefront of seismic design in the United States. The evolution of seismic design in California includes altering the design methodology as well as incorporating damage mitigation devices in structures. Recently, as part of the trend of earthquake damage mitigation, the California Department of Transportation (Caltrans) has embraced the use of bridge fragility models, particularly in post-event response programs. As part of the authors' project with Caltrans, fragility analysis is being explored as a possible design aid during the design process of a bridge, in addition to the use as a post-event tool.

The California Department of Transportation (Caltrans) seismic bridge design process specifies the design engineer to meet minimum requirements resulting in a bridge that should remain standing in the event of a Design Seismic Hazard (DSH) (Caltrans 2010). By following the guidelines set forth by the SDC, a design engineer should produce a bridge design that performs acceptably under anticipated seismic loads. However, the procedure set forth in the SDC is a prescriptive approach which does not provide quantitative information on how a bridge will perform under a given hazard. Therefore, there is a need for a methodology that will provide statistical information on how the bridge will perform for the given hazard level, and for demands beyond the hazard level. There is also a need for designers to have an understanding of the effects of certain design decisions on the probabilistic performance of a bridge.

The authors are involved with a project with Caltrans that will introduce probabilistic fragility analysis into the Caltrans design process and address the aforementioned shortcomings of the current design process. The motivation for this project is to improve the designer's understanding of the probabilistic performance of their bridge design in order to produce better designed bridges. To accomplish these goals, a new fragility method will be developed to produce bridge-specific fragility curves and to develop a design support tool to be implemented as a supplement to the design process of Caltrans. To develop bridge specific fragility curves, bridge design parameters that most affect the response of the bridge must be identified. This paper introduces the design parameters that will be used in the proposed fragility method and investigates the affect of the design parameters on the response of the bridge with a sensitivity study.

2. ANALYTICAL FRAGILITY ANALYSIS AND BRIDGE SPECIFIC FRAGILITY ANALYSIS METHOD

There are four main approaches to developing fragility curves, which are based on the origins of the damage data used in the generation of the curve. Empirical fragility curves use observed damage data from past earthquakes to determine the probability of damage to a structure. Judgmental fragility curves use the opinions of experts to determine the damage an earthquake ground motion would cause to a structure at a certain damage level. Analytical fragility curves use simulations of structural models to develop damage distributions based on a comprehensive analysis of the structure. Hybrid fragility curves combine data from different sources to create damage states (Jeong and Elnashai 2007). The fragility methodology that will be used in this work to develop bridge specific fragility curves is a type of analytical and simulation based fragility process. A graphical overview of the typical analytical method used to derive fragility curves where failure probability is conditioned solely on ground motion intensity is given in Figure 1.

The following describes a typical analytical fragility analysis to produce fragility curves. Analytical bridge models are analyzed with nonlinear time history analyses using a suite of ground motions specific to the region in which the structure will be built. Because this method uses bridge models and suites of real or synthetic ground motions instead of actual damage data, uncertainty in the results have to be considered and mitigated throughout the entire process. The risk due to uncertainty must be mitigated and kept within acceptable levels, as all uncertainty is impossible to eliminate. For a structural system analyzed under earthquake loads, uncertainty comes from the demand and capacity of the analysis (Ji, Elnashai and Kuchma 2007). The uncertainties from the demand on a system comes from the ground excitation, which includes the soil conditions, load path of the motions, and the random motions generated from the source of the quake. The uncertainty from the capacity of the system can originate from the material and geometric uncertainty, where the properties of the designed structure and materials, such as concrete strength and span length, are considered random for the built structure. However, the variability of the response of the system is much more susceptible to the ground motion variability than the material uncertainties (Kwon and Elnashai 2006). Nonetheless, the bridge material properties in the models are often taken as random variables and determined using appropriate distributions. The material properties will contribute, along with the ground motions, to the variability in the response.

Once the analyses are done on the bridge models using the suite of ground motions, the responses of each bridge component are collected, and probabilistic seismic demand models (PSDM) are determined describing the relationships between the component responses and a ground motion intensity measure, such as peak ground acceleration. From these models, the correlation between all of the component responses can be calculated, and a joint PSDM (JPSDM) can be found for the system. From this joint model, the system fragility can be found by performing a Monte Carlo simulation of the JPSDM and comparing the resulting demand values with the component capacities to determine the system failure at each damage level (Nielson and DesRoches 2007).

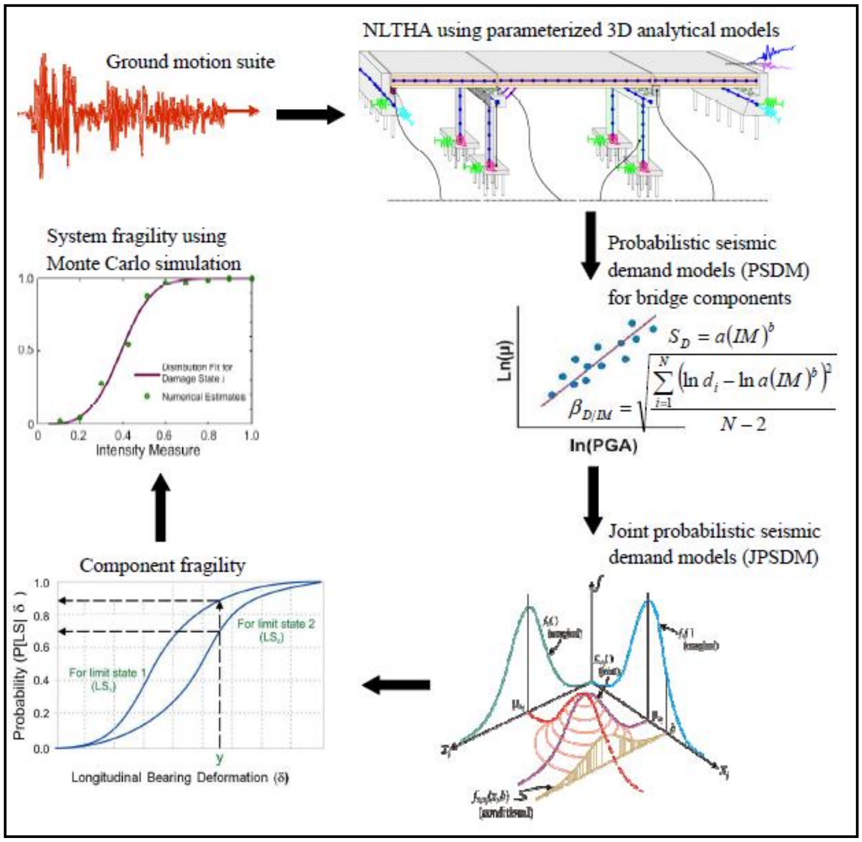

Figure 1: Illustration of the analytical fragility analysis method.

In past research (Nielson and DesRoches 2007)(Mackie and Stojadinović 2005), this approach has been used to develop fragility curves for a class of bridges, where the details of the bridges varied widely, or specific case-study bridges, where a deterministic model of a single bridge would be appropriate to use for analysis. However, to use this approach in a bridge specific application where the design details are unknown, many fragility curves would have to be developed for every possible combination of design details of a new bridge. That method would require a prohibitive amount of analyses and would be too computationally costly. Therefore, in developing bridge specific fragility curves, some aspects of the analytical fragility method will differ from the ways it's been developed in the past. The probabilistic seismic demand model (PSDM) will need to be modified to include more input variables than the ground motions intensity measure. In order to make the fragility curves specific to a bridge design, the PSDM will have to incorporate bridge design details into the formulation. Cornell, et al (Cornell, et al. 2002) developed a PSDM that directly relates an engineering demand parameter with a ground motion intensity measure, as shown in Eqn. 2.1. The demand, S_d, is determined only by the ground motion intensity measure, IM, chosen for the model, using a regression model on data produced from analytical models. In order to tailor the PSDM to specific bridge designs, other parameters should be included in the PSDM. Ghosh, et al. (Ghosh, Padgett and Dueñas-Osorio 2012) proposed a parameterized approach to developing a PSDM, as shown in Eqn. 2.2, which will be extended for use in this seismic design project. Some form of a bridge component response, Y, will be regressed against the ground motion intensity measure, IM, as well as a number of design parameters, DP_i. This would eventually lead to a fragility equation that is conditioned on the ground motion intensity measures as well as bridge design details, similar to Eqn. 2.3. The probability that the demand on the structure would exceed the capacity as defined by a limit state would be conditioned on the IM and the design parameter, DP_i. With this new definition of the fragility relationship, fragility curves specific to bridge design details can be produced.

$$\ln(S_d) = a + b * \ln(IM) \tag{2.1}$$
$$Y = \beta_0 + \beta_1(IM) + \beta_2 DP_1 + \cdots + \beta_{N+1} DP_N \tag{2.2}$$
$$P[\text{Fragility}] = P[\text{Demand} > \text{Capacity}(LS_i)|IM, DP_1, DP_2, .., DP_N] \tag{2.3}$$

3. DESIGN PARAMETERS

The fragility methodology briefly introduced in the previous section requires design parameters as conditioning variables. Thus, one need of this research is to find those design parameters which have the most effect on the responses of the different components of the bridge. The bridge design parameters introduced in this paper correspond to characteristics of the geometry of a bridge that were found to be important to monitor during the design process (Mackie and Stojadinović 2005), significant in the evolution of seismic design of bridges (Sahs, et al. 2008), as well as those suggested by the Caltrans team (Caltrans, Bridge Specific Fragility 2011). The bridge type that this research focuses on is a 2 span integral concrete box girder bridge. This bridge was chosen to test this method because it is a common type of bridge in California, representing about 8% of the total state bridge inventory. The five design parameters chosen for research are the longitudinal steel ratio of the columns, the volumetric ratio of transverse steel in the columns, the aspect ratio of the column height to column diameter, the ratio of superstructure depth to column diameter, and the ratio of span length to column height. Table 1 lists the design parameters used in this project and some effects on the behavior of a bridge by varying these parameters. Illustrations of these characteristics are given in Figure 2.

A sample of 40 bridge plans of the 2 span integral bridge type was taken from the California inventory to gather information on the design parameters present in modern designed (post 2000) bridges. The bridge plans were analyzed to extract details of the bridges in order to construct accurate finite element models based on real bridge data, and to extract design parameter details from each bridge. The minimum and maximum values of each design parameter were found in the sample of bridge plans, and set as initial ranges to be used in this research. Upon observing outliers in the data, adjusted minimum and maximum values were determined and given in Table 2. When constructing the demand model using an appropriate design of experiment (DOE), these values will be varied according to the DOE to create bridge models on which to perform nonlinear time history analyses will be and to extract component responses to determine statistically the effect of each design parameter on the response of the bridge.

Table 1: Description of design parameters used in this project.

Longitudinal Reinforcement ratio	A higher steel ratio stiffens and strengthens the column
Volumetric Ratio– measures the amount of transverse reinforcement	Determines the difference between unconfined and confined concrete strength, which determines the capacity of the component
Aspect Ratio– Column Height to Column Dimension Ratio	Increasing this ratio makes the structure more flexible
Superstructure Depth to Column Dimension Ratio	Increasing the depth makes the structure more stiff

Span length to column height ratio	Increasing the span length makes the structure more flexible

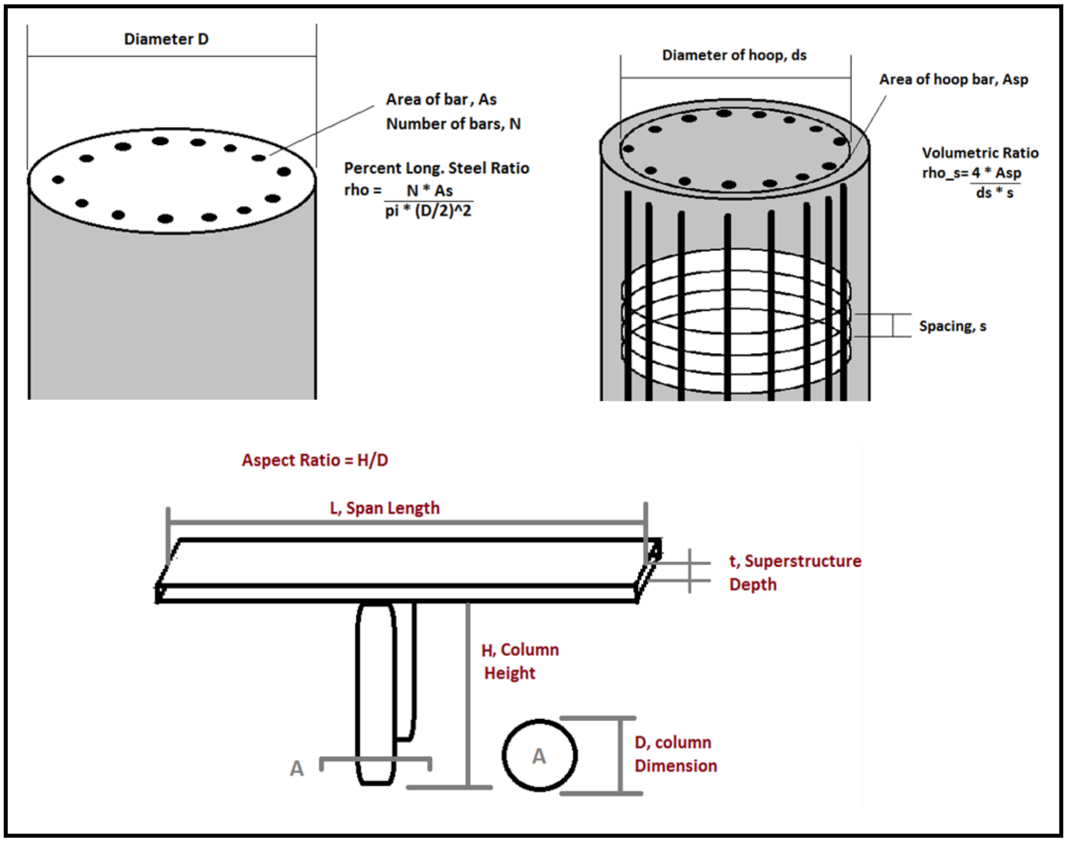

Figure 2: Illustration of design parameters.

Table 2: Values of the design parameters used in project.

Ranges of Design Parameters from Bridge sample					
	Aspect Ratio (H/D)	**Longitudinal Steel Ratio**	**Volumetric Steel Ratio**	**Span Length to Column Ht Ratio**	**Superstructure Depth to Column Diameter Ratio**
Minimum	2.47	0.98%	0.42%	2.20	0.71
Maximum	11.35	3.41%	1.43%	10.29	1.43
Median	3.82	1.71%	0.93%	6.83	1.03
Adjusted Min*	**2.50**	**1.00%**	**0.50%**	**4.50**	**0.80**
Adjusted Max*	**6.00**	**3.00%**	**1.40%**	**9.50**	**1.30**

* Note: These adjusted values represent the actual ranges of the design parameters used in this research.

4. SENSITIVITY STUDY OF DESIGN PARAMETERS

A sensitivity study was completed to test the effects of varying different design parameters on the response of key bridge components: columns, abutments and bearings. This investigation is a primary step towards the end goal of developing the bridge specific design framework that incorporates bridge fragility into the design checking process. After the set of design parameters is defined, a multi-parameter fragility methodology or process can be developed in order to produce individualized curves for a specific bridge design. The five design parameters introduced earlier were varied in a statistical manner to create bridge models for analysis in order to quantify the effects of each parameter on the response of the bridge system and components.

The base bridge model from which all of the bridge models used in the study builds upon was developed based on median values of bridge characteristics, excluding the defined design parameters. These median values of bridge characteristics, such as width of bridge and footing details, come from the analysis of the bridge plan sample described earlier. The base bridge is a two span integral concrete box girder bridge with zero skew or curve, two columns at the integral bent, and a seat-type abutment.

The sensitivity study was designed as a confirmatory experiment, in which the factors investigated have been suggested to be significant in previous studies (Kutner, et al. 2005). The factors in this case are the design parameters, and this experimental study was used to confirm the importance of each factor in determining the response of different bridge components. A design of experiment (DOE) was developed that would be able to determine the effects of each individual factor, as well as interactions between them. A two-level fractional factorial design was chosen as the DOE of choice for this study. A two-level fractional factorial experiment looks at each factor at two levels, usually the upper and lower bound of the factor range, and instead of having a full factorial design of 2^k experiments, where k is the number of factors, a subset, or fraction, of that number of experiments is developed with little loss of information on the main effects of the factors (Kutner, et al. 2005). Table 3 shows the schedule of factors that correspond to the values of the design parameters that will be used to create bridge models for this sensitivity study. A [-1] indicates the lower bound value, and [1] indicates the upper bound value. The upper and lower bounds were given in Table 2 as the minimum and maximum values of each factor from the bridge sample.

Each of the bridge models developed for each run from the DOE described earlier was subjected to 30 ground motions chosen from a suite of 120 broadband earthquake ground motions from the Pacific Earthquake Engineering Research Center (PEER) Transportation Research Program ground motions developed by Baker, et al. (Baker, et al. 2011) These 30 ground motions were chosen randomly from the 120 ground motions to provide a wide range of ground motion characteristics in order to evoke a range of responses from the analyses. The peak ground acceleration (PGA) and spectral acceleration at 1 second values of these 30 chosen ground motions are shown in Figure 3. As is shown, the ground motion set encompassed a wide range of ground motion intensity levels, ranging from less than 0.05g to 0.8g in terms of PGA. In total, 480 analyses of bridge models were performed to use in this sensitivity study.

Finite element bridge models were created and analyzed in OpenSees (Open System for Earthquake Engineering Simulation n.d.). Figure 4 shows a typical layout of the nodes and elements that define the bridge model. Non-linear beam column elements were used to define the columns of the bridge to be able to capture the nonlinear behavior. Elastic beam elements describe the deck elements, as the deck is not expected to perform nonlinearly. At the abutments, springs were used to simulate the interaction between the abutment and the soil, as well as the behavior of the bearings with the deck. Foundation springs simulate the response at the base of each column. These bridge models were analyzed using a nonlinear time history analysis.

Each model was subjected to 2 orthogonal ground motions at an incidence angle of zero input into the defined support nodes. Recorders defined in OpenSees recorded the deformation, displacement, force or stress specified at particular elements or nodes along the bridge in order to find the response of the bridge system after the analysis. These recorded responses serve as the data used to determine the effect of the design parameters on the response of the bridge.

Table 3: Design of experiment for sensitivity study.

	Design Parameter				
Run	Percent Long Steel	Volumetric Ratio	Aspect Ratio	Span to Height ratio	Depth to Diameter Ratio
1	1	-1	-1	1	1
2	-1	1	-1	1	1
3	-1	1	-1	-1	-1
4	1	-1	1	1	-1
5	-1	-1	1	-1	-1
6	1	1	-1	1	-1
7	-1	-1	1	1	1
8	1	1	1	-1	-1
9	-1	-1	-1	-1	1
10	1	-1	1	-1	1
11	1	1	1	1	1
12	1	-1	-1	-1	-1
13	-1	1	1	-1	1
14	-1	1	1	1	-1
15	-1	-1	-1	1	-1
16	1	1	-1	-1	1

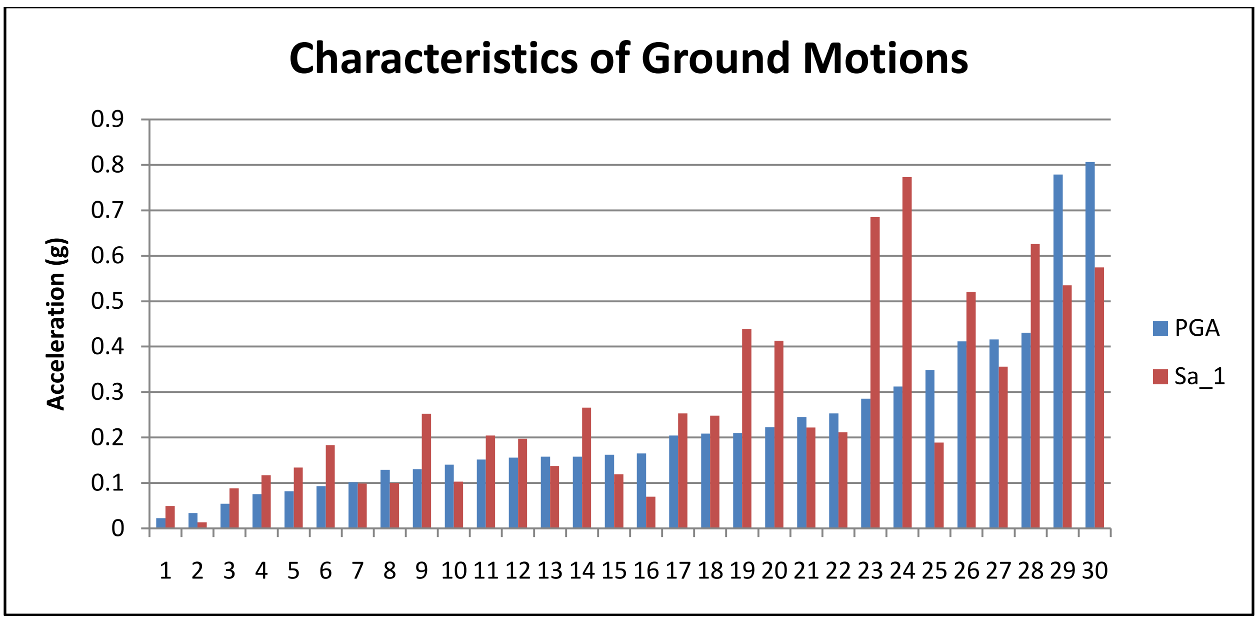

Figure 3: PGA and Sa1 values of ground motions used in sensitivity study.

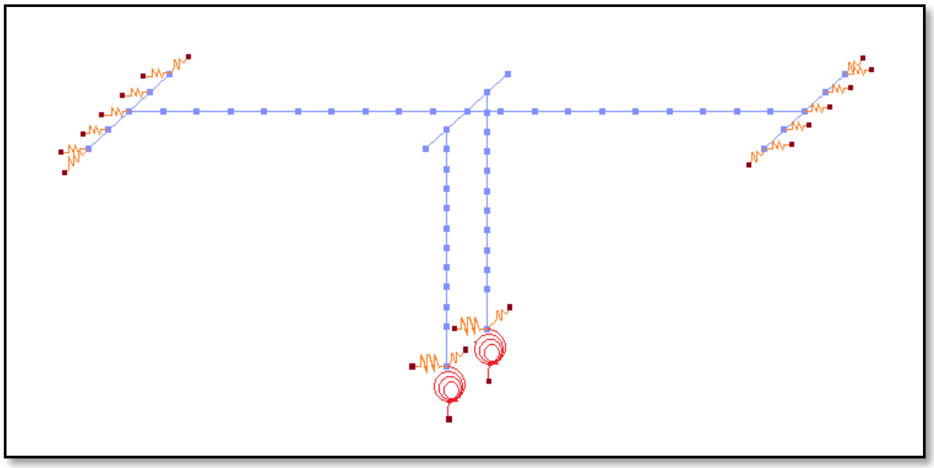

Figure 4: Typical OpenSees layout of 2 span bridge.

5. RESULTS OF SENSITIVITY STUDY

After all of the analyses were run in OpenSees, the recorded responses of the different bridge parameters were extracted to be used to determine the effect of the different design parameters on the component responses. The different component responses were then compared against the design parameters to determine the significance of the parameters on the responses. JMP software was used to conduct ANOVA tests, which are presented in this section (JMP the Statistical Discovery Software 2010).

In conducting ANOVA tests, a hypothesis is considered and tested using the F test. In this case, the null hypothesis (H_0) is that the coefficients of a regression relationship (β_1) are equal to zero, and therefore there is no regression relation between the response variable and the design parameter. The hypothesis tests and F statistic is computed per Eqn. 5.1 for a single variable regression (Kutner, et al. 2005). MSR is the mean regression sum of squares, MSE is the mean squared error of the regression, and [n-2] represents the number of degrees of freedom in the relationship. For this study, α is assumed to be equal to 0.05, which is a typical value used to test statistical significance. P-values are the probability of the calculated F statistic being greater than the F statistic at the defined alpha level.

$$
\begin{aligned}
&H_0 : \beta_1 = 0 \\
&H_a : \beta_1 \neq 0 \\
&F^* = MSR/MSE \\
&\text{If } F^* \leq F(1-\alpha; 1, n-2), \text{ conclude } H_0 \\
&\text{If } F^* > F(1-\alpha; 1, n-2), \text{ conclude } H_a
\end{aligned}
\tag{5.1}
$$

Table 4 shows the p-values from the ANOVA of six different bridge component responses for each design parameter. Every design parameter was shown to be statistically significant for one or more of the bridge component responses according to the test criteria defined earlier. The longitudinal steel ratio is significant in predicting column behavior, active and transverse abutment responses, and longitudinal bearing deformation. The transverse reinforcement ratio was found to be significant in predicting the passive and transverse abutment responses. The aspect ratio was significant for column behavior, active and passive abutment responses, and longitudinal bearing response. The span length to column height ratio was found to be significant in predicting the passive and transverse abutment responses, and longitudinal bearing response. The depth to diameter ratio was significant in the cases of column behavior, and all abutment responses.

Table 4: P-values of the design parameters from ANOVA.

P-values	***Bridge Component Response***					
Parameter	Column Curvature Ductility	Active Abutment Movement	Passive Abutment Movement	Transverse Abutment Movement	Longitudinal Bearing Deformation	Transverse Bearing Deformation
Longitudinal Steel Ratio	**0.0018**	**0.0498**	0.2277	**0.0004**	**0.0283**	0.0605
Trans Volumetric Ratio	0.3149	0.3283	**0.0032**	0.0539	0.6281	0.7479
Aspect ratio	**0.0001**	**0.0001**	**0.0001**	0.561	**0.0001**	0.2354
Span Length to Column Height Ratio	0.665	**0.0103**	**0.0001**	**0.0019**	**0.0063**	0.089
Deck Depth to Column Diameter Ratio	**0.0426**	**0.0326**	**0.0001**	**0.0116**	0.9123	0.8416

Based on this statistical information from the ANOVA, the five aforementioned design parameters were shown to contribute significantly to the prediction of component responses. The longitudinal steel ratio parameter was found to be significant to predicting the response of the column, active abutment, transverse abutment, and longitudinal bearing component responses. Likewise, the aspect ratio had a significant effect on 4 component response. The transverse reinforcement ratio was found to be significant to predicting the response of the passive abutment component response. As a result of this sensitivity study, it was determined that these five design parameters could be used in further research of developing bridge-specific fragility curves.

6. SUMMARY AND FUTURE WORK

The seismic design process of bridges in California is designed to ensure acceptable seismic performance for a design hazard level. It is lacking a performance based approach of determining how well a new bridge design performs at that design hazard level, as well as at any design level. The goal of the authors' project with Caltrans is to develop a performance based tool for the bridge design process using bridge-specific fragility analysis. Part of that research involves finding certain design parameters that most affect the performance of a bridge to use in the bridge-specific fragility method. The design parameters presented in this paper are critical in the design process of California Department of Transportation (Caltrans) bridge engineers. These design parameters will be used in a fragility methodology that will produce bridge specific fragility curves according to specific design aspects of the bridge design.

The statistical tests performed on the design parameters confirmed the significance of these parameters in determining the response of monitored bridge components. Four of the five design parameters were determined to have a significant influence on four of the component responses that were monitored from finite element analyses. Only one design parameter, the transverse reinforcement ratio, was determined to only have a significant impact on the response of one component response. As this sensitivity study of the design parameters has shown that these parameters have a significant impact on the response of the bridge, these parameters will be used in the next step of developing a bridge specific fragility methodology. For future work, as part of the project for Caltrans, the bridge specific fragility methodology will be developed that will incorporate a multi-parameter PSDM, as introduced earlier, into the analytical fragility method. The concept of metamodels will be used to determine an appropriate design of experiment that will detail the analytical bridge models in order to produce accurate regression models and PSDMs. Capacity models will be developed that are specific to bridges in California. Bridge specific fragility curves will then be developed from the new PSDM and California specific capacity model. The end product of this project is to develop a design support tool for Caltrans engineers that provide bridge specific fragility curves and aid in helping engineers make more performance-based decisions in the seismic design of bridges.

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