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Quantification of Modeling Uncertainty in an RC Bridge Column

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ABSTRACT

Various sources of uncertainty play a critical role in the safety assessment of engineering structures. While performance-based earthquake engineering (PBEE) framework recommends accounting for all sources of uncertainty, most applications are centered on ground motion record-to-record variability. This paper presents the results of modeling uncertainty quantification analysis of a reinforced concrete bridge column. Parent models are developed using two different (simple and advanced) modeling strategies. Sources of modeling uncertainty are propagated through the parent models to generate thousands of children models. An innovative intensifying artificial acceleration is used to perform the nonlinear transient simulations at different seismic intensity levels. The dispersion in the drift response is quantified for each family of models (children models associated with a specific parent model). These variabilities are further combined with material-related dispersion. The modeling uncertainties overshadow the material randomness. Finally, a series of regression analyses are performed to highlight the importance of each of the sources of modeling uncertainty and its contribution to the total variability. The results of this study can be used for model reduction in similar structures.

Introduction

The concept of uncertainty in the numerical simulation of structural systems has been taken into account in some of pioneer works on nuclear power plants [1]. Since the introduction of performance-based earthquake engineering (PBEE) framework by Pacific Earthquake Engineering Research Center (PEER), many modifications and expansions have been made to the framework. Despite these modifications, the uncertainty quantification (UQ) has always been an inseparable aspect of the PBEE framework. Researchers in the field of structural engineering use the following classification of UQ types [2]: aleatory (objective) uncertainty is presumed to be the intrinsic randomness of a phenomenon, and epistemic (subjective) uncertainty is due to lack of knowledge.

In the field of structural and earthquake engineering, three sources of uncertainties are typically considered in assessment of buildings: (a) Ground motion record-to-record (RTR) variability, which arises from the aleatory nature of ground motion selection and scaling. The RTR variability is a widely used source of uncertainty in seismic engineering and many researchers have quantified its impact through different methods, e.g.,

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incremental dynamic analysis; (b) Material uncertainty which mainly arises from variation in or lack of knowledge about the exact material properties (i.e., insufficient tests, time-dependent degradation); (c) Modeling uncertainty which accounts for assumptions that are typically used during the numerical simulation of a physical specimen. Modeling uncertainty, in contrast to the RTR and material randomness, is not well defined and lacks a unique definition. For example, [3] defines the modeling uncertainty by the extent to which the model represents the true structural response. On the other hand, [4] classifies the modeling uncertainty into four main categories: uncertainties in the measurement of physical quantities, uncertainty in the correlation between measurable physical quantities and constitutive model parameters, uncertainty in selecting a constitutive model, and uncertainty in the overall idealized model methodology.

This paper investigates the impact of various sources of modeling uncertainties on the overall response variation of a RC bridge column. Two modeling strategies are adopted: simple and advanced. For each of them, the contribution of potential modeling variabilities is discussed on overall dispersion in response quantity. This study seeks to identify the significant uncertain variables, their contribution, and potential feature reduction methods towards establishing an efficient UQ framework for RC structures.

Developing Parent and Children Models

The case study is selected to be a circular bridge column tested at the University of California, San Diego [5] as seen in Figure 1. A large concrete block is attached to the top to simulate the bridge superstructure. Two general strategies have been adopted to develop the numerical model in OpenSees: lumped (L) and distributed (D) plasticity models. The lumped plasticity model is based on plastic hinge model and the distributed plasticity model is based on fiber model with force-based formulation. To remove the bias due to ground motion RTR variability, and also to investigate the response of the system at different seismic intensities, an artificially generated intensifying acceleration record is applied to the numerical models. Details about this technique, its interpretation, and validation compared to conventional nonlinear time history analyses can be found in [6].

Table 1. Summary of modeling-related random variables and their range for each parent model. L: lumped plasticity model, D: distributed plasticity model (☻ indicates inclusion in the parent model)

Random variable	**Range/outcome of RV**	**L**	**D**
Number of Gauss integration points	3, 5, 7		☻
Damping ratio	1%, 2.5%, 5%	☻	☻
Damping model	Rayleigh and Modal	☻	☻
Geometric transformation	Corotational, P-Delta, and Linear	☻	☻
Mass discretization	Distributed, Lumped	☻	
Cross-sectional discretization	Fine, and Coarse		☻
Concrete constitutive model	Concrete02, Concrete04 and Concrete07		☻
Steel constitutive model	SteelMPF, ReinforcingSteel, Steel4		☻
Concrete regularization	Yes, No		☻
Steel regularization	Yes, No		☻
Column moment of inertia	0.7 $I_{elastic}$, $I_{effective}$	☻	
Cyclic deterioration parameter	Detailed, Simplified	☻	
(Lumped plasticity) model formulation	ASCE, NIST	☻	
Plastic hinge length	7.5% L, 15% L	☻	

Table 1 presents the modeling-related random variables (RVs) that are integrated into the parent models to create the children models. For each RV, a set of categorical values or options are used. It is notable that not all these RVs are applicable in a single modeling technique. For example, the type of concrete or steel model can be used only for fiber distributed plasticity models (a.k.a. advanced model), while the length of plastic hinge (a.k.a. simple model) is used for lumped plasticity models. With ten and nine RVs for simple and advanced parent models, respectively, a total of 5,184 combinations are developed for the parent fiber model, while the number of plastic hinge models are composed of 3,456 combinations.

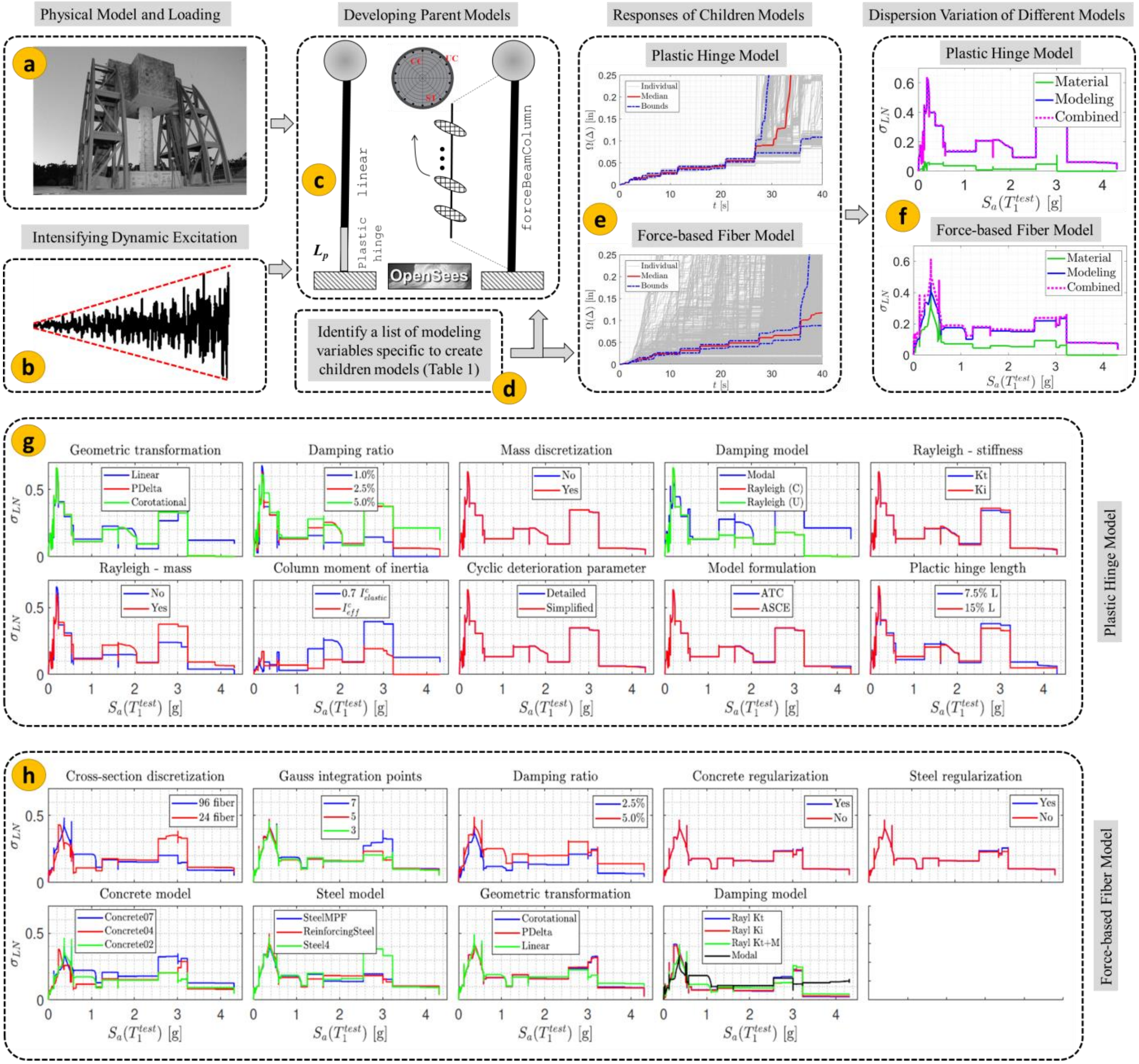

Figure 1. Description of case study and results. (a) Physical model, (b) applied acceleration function, (c) two parent models, (d) incorporation of modeling uncertainties and generating children models, (e) drift response of children models, (f) drift dispersion of children models, (g) detailed dispersion variation of lumped plasticity models, and (h) detailed dispersion variation of distributed plasticity models.

Results and Discussion

The model response is evaluated from the linear elastic range up to collapse using the intensifying dynamic load Figure 1(e) presents the variation of drift values in children models including their median and bounds. Figure 1(f) compares the dispersion (quantified as the logarithmic standard deviation) in children models with (i) modeling uncertainty only, (ii) material uncertainty only, and (iii) combined uncertainty with SRSS method. The uncertainty quantification study with only material randomness has been reported in [7]. Material uncertainty models have the lowest dispersion in both parent models, while modeling uncertainty has the highest dispersion. Since the lumped plasticity model does not use the direct material properties, they underestimate the material dispersion compared to the advanced model (i.e., fiber distributed model). The SRSS combination shows larger dispersion values than direct combination (8% in average, and can be as large as 25%). Incorporating the material randomness in modeling uncertainty analysis does not increase the uncertainty significantly as the modeling uncertainty dominates the randomness.

Figures 1(g) and 1(h) illustrate the variation of dispersion in the drift response associated with different modeling RVs. As shown in to Figure 1(g), the fine cross-section discretization (i.e., 96 fibers) causes more dispersion than a coarse discretization (i.e., 24 fibers) at lower seismic intensity levels. At higher intensity levels, the coarse discretization has higher dispersion. The number of Gauss integration points is important at higher seismic intensity levels. Higher damping ratio causes higher dispersion for the entire range of applied dynamic load. Variation in dispersion due to concrete models is larger than steel models. Modal damping causes higher dispersion compared to different combinations of Rayleigh damping.

Further, as illustrated by Figure 1(f), a higher damping ratio creates larger dispersion for fiber models. Also, the modal damping causes higher dispersion compared to Rayleigh models. For lumped plasticity model, the impact of stiffness- and mass-proportional Rayleigh damping model is distinguished. While the variation in the stiffness component does not cause any change in dispersion value, the inclusion of the mass-proportional component does increase the dispersion. The choice of column moment of inertia (i.e., column cracked stiffness assumption) is probably the most notable RV in this list as it causes the highest dispersion along the entire seismic intensity range of interest. Variability in cyclic deterioration parameter (i.e., simplified or detained relations) and the analytical formulation to calculate the parameters required for the BeamWithHinges model in OpenSees do not affect dispersion values. Finally, the impact of plastic hinge length is minor.

Conclusions

This paper presented a component-level framework for quantification of the impact of modeling uncertainty on the response of RC bridge columns. The proposed framework is generic and can be applied to any component-level models. The epistemic uncertainties were decomposed into material and modeling RVs. The impact of each uncertainty source was studied separately, and their combined effect was quantified. This study found that modeling strategy and the associated variability are very important, and may cause large variance in drift response. The modeling uncertainty clearly overshadows the material randomness.

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