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# QUANTIFICATION OF UNCERTAINTIES IN THE RESPONSE OF BEAM-COLUMNS IN STEEL MOMENT FRAMES

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## ABSTRACT

Various sources of uncertainties including material, modeling, and record-to-record (RTR) uncertainties can have a significant influence on prediction of earthquake-induced damage and estimates of the collapse risk of a building obtained through the performance-based earthquake engineering framework. As a first-step toward quantifying the influences of these uncertainties on the collapse risk of buildings, this paper systematically quantifies the influence of material, modeling, and record-to-record uncertainties on the performance of structural steel beam-columns. In this study, material uncertainty is characterized by probability distribution functions (PDFs) developed using available material coupon data. These PDFs are employed in stochastic simulations to quantify the influence of material uncertainty on the calculated maximum drift ratio of beam-columns. The influence of employing different modeling techniques and software packages, i.e., modeling uncertainty, on the predicted response of steel beam-columns is also quantified, by development of multiple nonlinear models for a beam-column tested experimentally. The dynamic analysis results of the nonlinear models are used to develop a set of PDFs representing the variability in the drift response due to the modeling uncertainty. The uncertainty in the applied ground motions, i.e., RTR uncertainty, is quantified by performing Incremental Dynamic Analysis on an analytical model of a beam-column specimen, which is calibrated to and validated against the experimental results. The variation in the response of the beam-column is quantified via a set of PDFs as well as means, medians, and standard deviations of the drift response for each source of uncertainty at multiple intensity measures ( $S_a(T_1)$ ). The results show the record-to-record uncertainty as having the greatest and material uncertainty as having the least influence on the uncertainty in the predicted maximum drift ratio.

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# Quantification of Uncertainties in the Response of Beam-Columns in Steel Moment Frames

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## ABSTRACT

Various sources of uncertainties including material, modeling, and record-to-record (RTR) uncertainties can have a significant influence on prediction of earthquake-induced damage and estimates of the collapse risk of a building obtained through the performance-based earthquake engineering framework. As a first-step toward quantifying the influences of these uncertainties on the collapse risk of buildings, this paper systematically quantifies the influence of material, modeling, and record-to-record uncertainties on the performance of structural steel beam-columns. In this study, material uncertainty is characterized by probability distribution functions (PDFs) developed using available material coupon data. These PDFs are employed in stochastic simulations to quantify the influence of material uncertainty on the calculated maximum drift ratio of beam-columns. The influence of employing different modeling techniques and software packages, i.e., modeling uncertainty, on the predicted response of steel beam-columns is also quantified, by development of multiple nonlinear models for a beam-column tested experimentally. The dynamic analysis results of the nonlinear models are used to develop a set of PDFs representing the variability in the drift response due to the modeling uncertainty. The uncertainty in the applied ground motions, i.e., RTR uncertainty, is quantified by performing Incremental Dynamic Analysis on an analytical model of a beam-column specimen, which is calibrated to and validated against the experimental results. The variation in the response of the beam-column is quantified via a set of PDFs as well as means, medians, and standard deviations of the drift response for each source of uncertainty at multiple intensity measures ( $S_a(T1)$ ). The results show the record-to-record uncertainty as having the greatest and material uncertainty as having the least influence on the uncertainty in the predicted maximum drift ratio.

## Introduction

In recent years, the development of a probabilistic framework as part of the Performance-Based Earthquake Engineering (PBEE) philosophy, has provided a mechanism for incorporating the influences of uncertainty into seismic assessment of structures. Three main sources of uncertainty contribute to uncertainty in the seismic assessments: (1) uncertainty due to inherent variation of the material properties (i.e., material uncertainty); (2) uncertainty embedded in simulations (i.e., modeling uncertainty); and (3) uncertainty due to the selected ground motion (GM) used in the analysis (i.e., record-to-record (RTR) uncertainty). Quantification of these three sources of uncertainty plays an important role in evaluating the accuracy of structural assessments. Of these sources of uncertainty, the influence of the RTR uncertainty on performance assessments of

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structures is reasonably well established; however, the influences of material and modeling uncertainties have not yet been systematically integrated into PBEE.

The influence of material uncertainty on the structural response is often ignored in the seismic assessment of structures by using determinant material properties, which in practice may represent mean, lower bound or expected material properties. In most previous studies concerned with quantifying material uncertainty, the influence of material uncertainty is lumped together with the modeling uncertainty [e.g., [1-2]], and is not separately quantified. This study quantifies the sole influence of material uncertainty on the response of a steel beam-column for a given modeling approach. Past research has also studied the impact of modeling uncertainty on the seismic assessment of buildings by varying modeling parameters such as component strength and stiffness, but within a single model developed using a unique modeling approach, for example, lumped plasticity [2]–[4]. This approach, however, neglects uncertainties stemming from the employed modeling approach or software [5]. In other words, the uncertainty calculated based on this approach is specifically conditioned on the use of that unique modeling technique. This paper does account for modeling uncertainty, by varying the properties of the building component using multiple different software packages and modeling approaches [6]. To the authors' knowledge, this aspect of uncertainty has not yet been investigated for steel beam-columns. The RTR uncertainty stems from variation in the structural response or mode excited by GMs with different frequency content or other characteristics. RTR uncertainty is incorporated in the PBEE framework through development of robust techniques for GM selection and scaling [2]. This study uses Incremental Dynamic Analysis (IDA) to quantify the influence of RTR uncertainty on the response of the steel beam-column.

Understanding the relative influences of various sources of uncertainty on the response of the structure will help to identify their importance in quantifying the overall uncertainty in the structural response. It is generally assumed that the influence of RTR uncertainty outweighs that of material and modeling uncertainty. However, no systematic study has been undertaken to quantify and compare the relative influences of these three sources of uncertainty.

### **Methodology of the Study**

This study quantifies the influence of each of three sources of uncertainty (material, modeling, and RTR) on the drift response of a steel beam-column. The relative importance of each source of uncertainty is quantified by conducting multiple nonlinear time history analyses that reflect variations in the material properties, modeling approaches, or input GMs for the selected steel beam-column. The W24×146 section tested by Elkady and Lignos [7] is selected for this study, as a cross-section that is frequently used in structural engineering design practice.

Different acceleration-time history GM records, which vary in terms of intensity level, shape of the record, and frequency content, can be selected for performing nonlinear time history response analysis. One might expect that uncertainty in the response of a structure would increase as the level of excitation increases; however, there is no guarantee that a particular record will induce a sufficiently large excitation to push the structural response into the highly-nonlinear range. To overcome this issue without the need for repeating the nonlinear time history analysis at increasing excitation levels, the nonlinear dynamic analysis is conducted using an Endurance Time

Acceleration Function (ETAF) [8]. The ETAF is an intensifying dynamic load that shakes the structure from a low- to high-excitation levels. Dynamic analysis conducted using the ETAF acceleration time-history is equivalent to nonlinear dynamic pushover analysis, where the structural response ranges from elastic to highly-nonlinear, and finally to collapse. Over a given period of time, the response spectrum of the ETAF increases proportionately with a selected target spectrum. Fig. 1(a) shows the acceleration-time history of the selected ETAF, and Fig. 1(b) shows the response spectrum of the record at the target times indicated in Fig. 1 (a). Three target times are selected here to represent various ground motion intensity levels, which result in a range of responses of the numerical model.

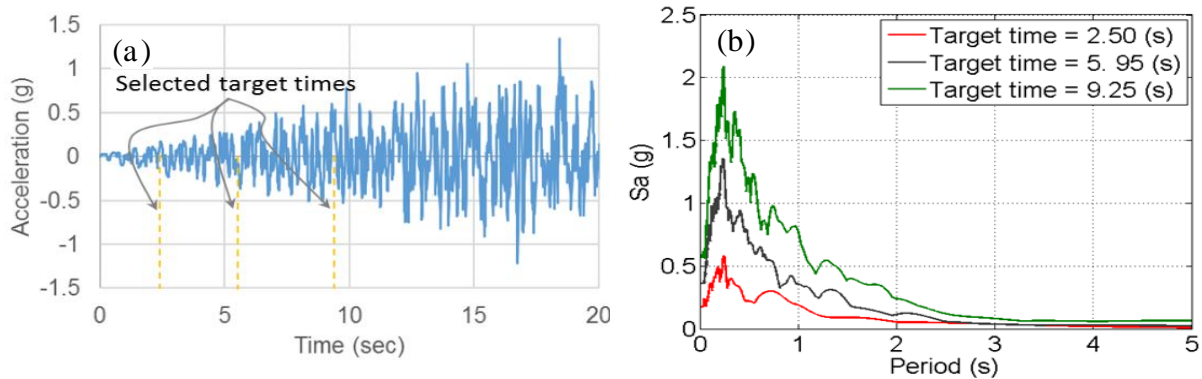


Figure 1. (a) Acceleration-time-history for the selected ETAF, and (b) the response spectrum of the selected ETAF at three target times of 2.5 s, 5.95 s, and 9.25 s.

The material uncertainty is quantified for ASTM A992 [9] steel based on a database of 73 samples. The material uncertainty is represented by probability distribution functions (PDFs) selected using the Kolmogorov-Smirnov (K-S) test to measure their goodness-of-fit [10]. A set of  $n$  realizations are generated to capture the uncertainty in the population of material properties of the steel used in the selected beam-column. Nonlinear time-history analysis is conducted for each realization, on a nonlinear model calibrated to the experimental test results. The maximum drift ratios are recorded at different excitation levels (target times). These drift ratios represent the variation (uncertainty) in the calculated drifts due to the variation in the material properties, while the other two sources of uncertainty are held constant by using the same nonlinear model and the ETAF acceleration record. The drift ratios are employed to quantify the mean, median, and dispersion in the drift results.

To quantify the modeling uncertainty, twelve nonlinear models are developed for the steel beam-column. These models differ in terms of their modeling formulation and resolution, i.e. high-fidelity, fiber, or lumped plasticity, the software package performing the calculation, and their modeling parameters (such as the assumed plastic hinge length), while holding the material properties and record-to-record uncertainty constant between analyses. These analyses are intended to isolate and quantify the individual influence of variations in modeling uncertainty on the response of the column. These models are developed by three different individuals, and each is without any calibration to the experimental results. The models are analyzed for the selected ETAF record, and the maximum drift ratios at various excitation levels (target times) are recorded and employed to quantify the modeling uncertainty in the selected steel column.

The RTR uncertainty is quantified using incremental dynamic analysis [11], where multiple nonlinear analyses are performed on a single calibrated model at different levels of seismic excitation, while holding the material properties and the analysis-type (and resolution) constant between analyses. The variation in the maximum drift ratios is calculated as a function of GM intensity, i.e.,  $S_a(T_1)$ . The distributions in the maximum drift ratio for three sources of uncertainty, as well as additional statistical information associated with each distribution are computed at the multiple excitation-levels and compared against one another.

### Material Uncertainty

A database comprising 73 stress-strain curves collected from 73 individual steel material coupon tests is compiled for three grades of ASTM A992 structural steel. Data for the grade A992 steels were compiled from a set of relatively light wide-flange sections tested by [12], and from relatively heavy wide-flange sections tested by [7] and [12]. From the stress-strain curve resulting from each steel coupon test, six material parameters were extracted: the modulus of elasticity  $E$ , yield strength  $\sigma_y$ , yield strain  $\epsilon_y$ , ultimate tensile strength  $\sigma_u$ , uniform strain  $\epsilon_u$ , and elongation at fracture  $\epsilon_f$  (Fig. 2). The modulus of elasticity is determined as the slope of the linear regression of the initial portion of the stress-strain curve between 20 % and 60 % of the upper-yield strength. The yield strength is determined using the 0.2 % offset method (employing the calculated modulus of elasticity). The uniform strain and the ultimate tensile strength were determined as the strain and stress, respectively, at the peak of the engineering stress-engineering strain curve. The fracture strain is determined as the final strain value of the engineering stress-strain curve.

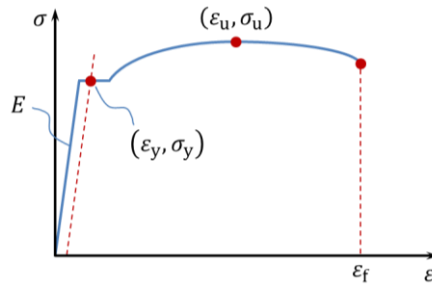


Figure 2. Schematic of material parameters extracted from each stress-strain curve.

As described above, a statistical distribution is fitted to the histogram of the values for each material parameter to capture its natural uncertainty. In addition to the individually fitted distributions, the material parameters were also assembled into a correlation matrix, so that the covariance between each material parameters could be evaluated. A total of 100 realizations are generated for the material parameters considering the multivariant correlation among parameters.

To isolate and characterize the influence of only the material uncertainty on the response of the column, 100 analyses are conducted while varying only the material properties for the calibrated lumped plasticity model developed in OpenSees [13], holding the analysis-type (and resolution) and the RTR uncertainty constant between analyses. The maximum drift ratios at multiple excitation levels are computed to quantify the uncertainty in the drift ratios due to material uncertainty. It is acknowledged here that the impact of material uncertainty will be a function of the modeling approach used in this study.

## Modeling Uncertainty

The W24×146 column tested by Elkady and Lignos [7] is employed to quantify modeling uncertainties. The column has a length of 13 ft (3.96 m), an elastic modulus of 29,000 ksi (200 GPa), and a moment of inertia of 4580 in<sup>4</sup> (1.91×10<sup>9</sup> mm<sup>4</sup>). The column is fixed at its base and has a fixed roller at its top, giving an initial flexural stiffness of 419.8 k/in (73.52 kN/mm). The mass of 10.63 k-s<sup>2</sup>/in (1861 Mg) is assigned at the top of the column to give a period of vibration of 1.0 s. A critical damping ratio of 2 % is assumed for the column. Geometric nonlinearity is based on the gravity load of 473 kip (2104 kN) applied at the top of the column. Material nonlinearity is addressed using plastic hinges, where applicable, located at the ends of the column. Twelve models are developed using different modeling techniques and software packages. The plastic hinges are modeled using either lumped plasticity or distributed plasticity.

### **Model 1: OpenSees with Elastic-Perfectly-Plastic Material Lumped Plasticity Model**

The uniaxial STEEL01 material in OpenSees with input moment-curvature relationship is used to model the column with two plastic hinges at 6 in (152 mm) away from the ends. This offset allows capturing the plasticity over the full curvature length. The plastic hinges exhibit elastic-perfectly-plastic relationship with a moment capacity of 25,080 k-in (2834 kN-m) and no strength loss.

### **Model 2: OpenSees with Lumped Plasticity Model - BILIN**

The uniaxial BILIN material in OpenSees with moment-curvature relationship as shown in Fig. 3(a) is used to model the column with two plastic hinges located 6 in (152 mm) away from the ends. The modeling parameters are computed based on empirical equations in [14] with a minor modification; the equation for calculating the effective yield strength is modified such that it does not account for cyclic hardening. Kinematic hardening with strength loss is included in the model with no cyclic degradation.

### **Model 3: OpenSees with ASCE41-Backbone Material Lumped Plasticity Model**

The uniaxial BILIN material in OpenSees with moment-curvature relationship based on ASCE/SEI 41 [15] as shown in Fig. 3(b) is used to model the column with two plastic hinges located 6 in (152 mm) away from the ends. Kinematic hardening with strength loss is included in the model with no cyclic degradation.

### **Model 4: OpenSees with Lumped Plasticity Model - CLOUGH**

The uniaxial CLOUGH material in OpenSees with moment-rotation relationship as shown in Fig. 3(c) is used to model the column with two plastic hinges having no offset. The modeling parameters are computed based on empirical equations in [14]. Kinematic hardening with strength loss is included in the model with no cyclic degradation.

### **Model 5: OpenSees with 12-Inch-Fiber Distributed Plasticity Model**

The uniaxial STEEL02 material in OpenSees is used to model the column with 12.8 in (325 mm) fibers at the ends. These fibers have the stress-strain relationship as shown in Fig. 3(d). Isotropic hardening with strength loss is included.

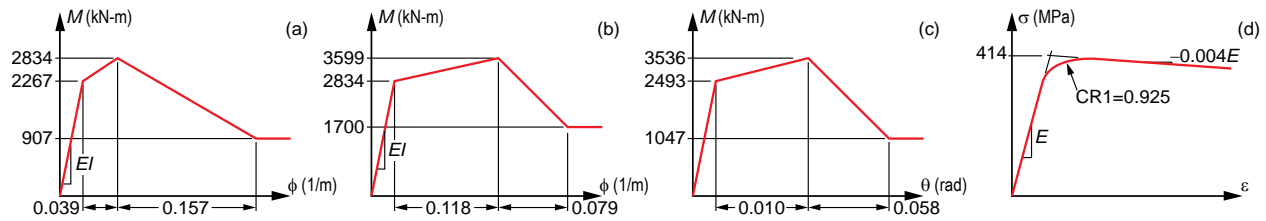


Figure 3. Moment-rotation backbone curves for OpenSees models.

### Model 6: OpenSees with 25 Inch Fiber Distributed Plasticity Model

This model is the same as that in Model 5, but with 25.6 in (650 mm) fibers at the ends.

### Model 7: Perform-3D with Elastic-Perfectly-Plastic Material Lumped Plasticity Model

The steel column model with  $P$ - $M$  interaction in Perform-3D is used, along with two plastic hinges at 6 in (152 mm) from the column ends. These plastic hinges exhibit elastic-perfectly-plastic behavior with a moment capacity of 25,080 k-in (2834 kN-m) and no strength loss.

### Model 8: Perform-3D with Cyclic Backbone Material and Lumped Plasticity

The column model is the same as that in Model 7, but the plastic hinges exhibit the moment vs. plastic rotation relationship shown in Fig. 4(a). Kinematic hardening with strength loss is included in the model with no cyclic degradation.

### Model 9: Perform-3D with Monotonic Backbone Material and Distributed Plasticity

The fiber column model in Perform-3D is used with fibers having 12 in (305 mm) lengths at the column ends. These fibers exhibit the stress vs. plastic strain relationship based on the calibrated monotonic backbone curve [14] as shown in Fig. 4(b). Kinematic hardening with strength loss is included in the model.

### Model 10: LS-DYNA with Elastic-Perfectly-Plastic Material and 12 Inch Finite Element

The Integration Beam element in LS-DYNA [16] with 21 integration points is used to model the column with two plastic hinges having 12 in (305 mm) finite elements at the column ends. These elements exhibit elastic-perfectly-plastic behavior with a yield stress of 60 ksi (414 MPa) and no strength loss.

### Model 11: LS-DYNA with Monotonic Backbone Material and 12 Inch Finite Element

The Integration Beam element in LS-DYNA with 21 integration points is used to model the column with two plastic hinges having 12 in (305 mm) finite elements at the column ends. These elements exhibit the stress vs. plastic strain relationship shown in Fig. 4(c). Isotropic hardening and strength loss are included in the model.

### Model 12: LS-DYNA with Monotonic Backbone Material and 24 Inch Finite Element

The Integration Beam element in LS-DYNA with 21 integration points is used to model the column with two plastic hinges having 24 in (610 mm) finite elements at the column ends. These elements exhibit the stress vs. plastic strain relationship shown in Fig. 4(d). Isotropic hardening and strength loss are included in the model.

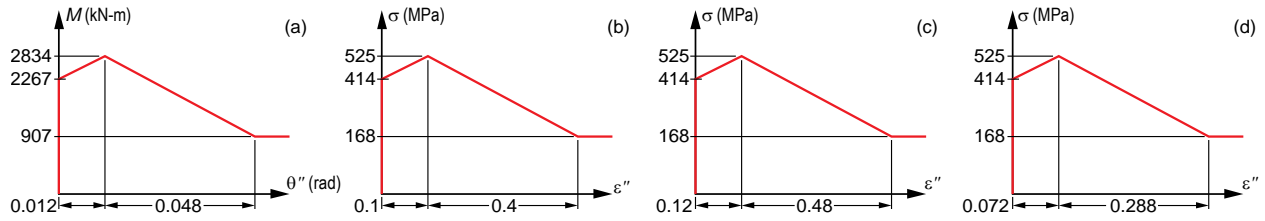


Figure 4. Stress-plastic strain backbone curves for Perform-3D and LS-DYNA models.

Each of the 12 models is then subjected to the ETAF GM to investigate the uncertainty in the computed drift ratios of the column due to modeling uncertainty.

### Record-to-Record Uncertainty

The nonlinear model developed using the measured material properties and the lumped plastic hinges based on the CLOUGH parametric equations (i.e., Model 4 above) is calibrated to the experimental results to minimize the influence of modeling uncertainty in the quantification of RTR uncertainty. The calibrated model is analyzed for 44 GM records in the FEMA P-695 far-field set [17]. The IDA results of the nonlinear model are presented in Fig. 5. This figure shows how the response of the same nonlinear model varies when different GM records, having different frequency content and characteristics, are used for the analysis. The FEMA P-695 set is used here for illustration. Using the IDA curves, the uncertainty in the calculated drift values is quantified at any intensity level,  $S_a(T_1)$ , in terms of a PDF, as shown in Fig. 5. As the intensity level increases, the uncertainty in the drift ratio increases.

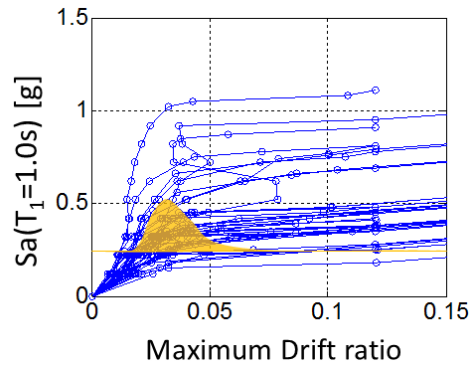


Figure 5. Incremental dynamic analysis results for OpenSees model calibrated to the cyclic test. [The distribution function is intended to schematically illustrate the uncertainty in the drift ratios at a particular intensity level].

The distribution of drift responses of the steel beam-column due to material, modeling, and RTR uncertainty at three excitation levels,  $S_a(T_1) = 0.20, 0.35, \text{ and } 0.75 \text{ (g)}$ , is shown in Fig. 6 using lognormal PDFs. The best-fit distribution based on the K-S test for various sources of uncertainty and even for the same source of uncertainty but at different excitation levels may differ. The lognormal distribution is selected here since it is commonly used in the field of structural engineering to represent the uncertainty in the drift response of structures. Fig. 6(a) shows the PDFs fitted to the maximum drift response of the models developed to represent the uncertainty in the material properties, modeling approaches, and GM characteristics at  $S_a(T_1)=0.20 \text{ g}$ . Fig. 6(a) shows that at the low-level excitation, the variation in the material properties of the column leads



to the least variability in the response, as indicated by a narrowest-width of the distribution, while the RTR variability leads to the largest variability, indicated by the widest width of the distribution, among the three sources of uncertainty. Fig. 6(b)-(c) shows similar distributions at the higher excitation levels of 0.35 and 0.75 (g). These figures show that the RTR and material uncertainties lead to the largest and smallest contributions to uncertainty in the calculated drift response of the column, respectively, regardless of excitation level.

Fig. 6(d) overlays the column responses from Fig. 6(a)-(c) to demonstrate that as the excitation level increases, the uncertainty in the predicted drift ratio due to the individual sources of uncertainty increases. This trend is expected, since as the response of the structure becomes more nonlinear, the stiffness of the model decreases and the drift response becomes more sensitive to the input demand parameters such as acceleration. In other words, minor changes in the input parameters lead to significant changes in the drift response as the structural response becomes highly nonlinear. In terms of modeling uncertainty, the variation of predictions between various models increase as the amount of nonlinearity increases due to the high sensitivity of the drift to acceleration when in the nonlinear range. In addition, the response of the column in the nonlinear range is more complicated and less understood in comparison with the linear range. In terms of material uncertainty, two factors contribute to this trend: (1) the uncertainty associated with the ultimate tensile strength and uniform strain are larger than those for the modulus of elasticity and yield stress (i.e., the uncertainties in the inelastic material properties are larger than those for the elastic material properties), and (2) the increased numbers of cycles as the level of excitation increases leads to an accumulation the small differences in material properties, leading to increased dispersions in the hysteretic response of the column.

Fig. 6(d) also shows that considering modeling uncertainty, in comparison with solely considering material uncertainty leads to a shift in the median drift response toward higher drift values. This shift in the median response becomes even more apparent by comparing modeling to RTR uncertainty. Fig. 6(d) demonstrates that considering RTR uncertainty leads to a significant increase in the computed mean drift response relative to only considering material or modeling uncertainties.

Table 1 summarizes the mean, median, and standard deviation of the drift response calculated due to material, modeling, and RTR variabilities, at three excitation levels,  $S_a(T_1) = 0.20, 0.35, \text{ and } 0.75$  (g). This table represents the statistical parameters for the probability distribution functions presented in Fig. 6 (a-c). The drift statistical parameters are computed using a lognormal distribution. The mean ( $\mu$ ) and median ( $\bar{\mu}$ ) are computed according to Eq. 1, where  $\bar{u}_{lnx}$  is the mean of the natural logarithm of drift values, and  $\sigma_{lnx}$  is the standard deviation of the natural logarithm of drift values (reported in Table 1).

$$\begin{aligned}\mu &= e^{\bar{u}_{lnx}} * e^{\frac{\sigma_{lnx}^2}{2}} \\ \bar{\mu} &= e^{\bar{u}_{lnx}}\end{aligned}\tag{1}$$

Trending from material to modeling and RTR uncertainty, the mean and median of the calculated drift ratios increase at each excitation level. The results in Table 1 also show that the computed standard deviation due to RTR variability is about 1.8 to 4.5 times and 6.5 to 14.5 times greater than that for modeling and material variabilities, respectively. This finding shows that the influence

of RTR variability on the uncertainty of the computed drift results is more significant than that for the material and modeling variabilities.

Table 1 reports that the standard deviation due to RTR variability decreases as we move from the  $S_a(T_1) = 0.35$  (g) to 0.75 (g). This observation is counterintuitive, and does not match with the results shown in Fig. 6(d). The reason for the lower standard deviation at higher excitation level is that, at the higher excitation level more records lead to collapse, and as a result most of the analyses result in an ultimate drift ratio of 15 % (preset in the analysis), which influence calculation of standard deviation. This observation shows that the representation of the uncertainty results in terms of lognormal distribution, may unwittingly lead to neglecting important information related to quantification of uncertainty. Thus, it is critical to use information on the proportion of simulations that lead to collapse of the structure in conjunction with other statistical parameters, when quantifying the uncertainty.

The last column in Table 1 reports the total uncertainty as the square-root-of-sum-of-squares of the uncertainties (standard deviations) due to material, modeling, and RTR variabilities, as suggested in FEMA P-695 [17]. Comparing the total uncertainty in the drift response to the uncertainty due to RTR variability shows that the total uncertainty is about 2 to 15% bigger than that for RTR variability. This small difference is due to the significant difference in the magnitude of the standard deviation computed for RTR variability in comparison with that for material and modeling variabilities.

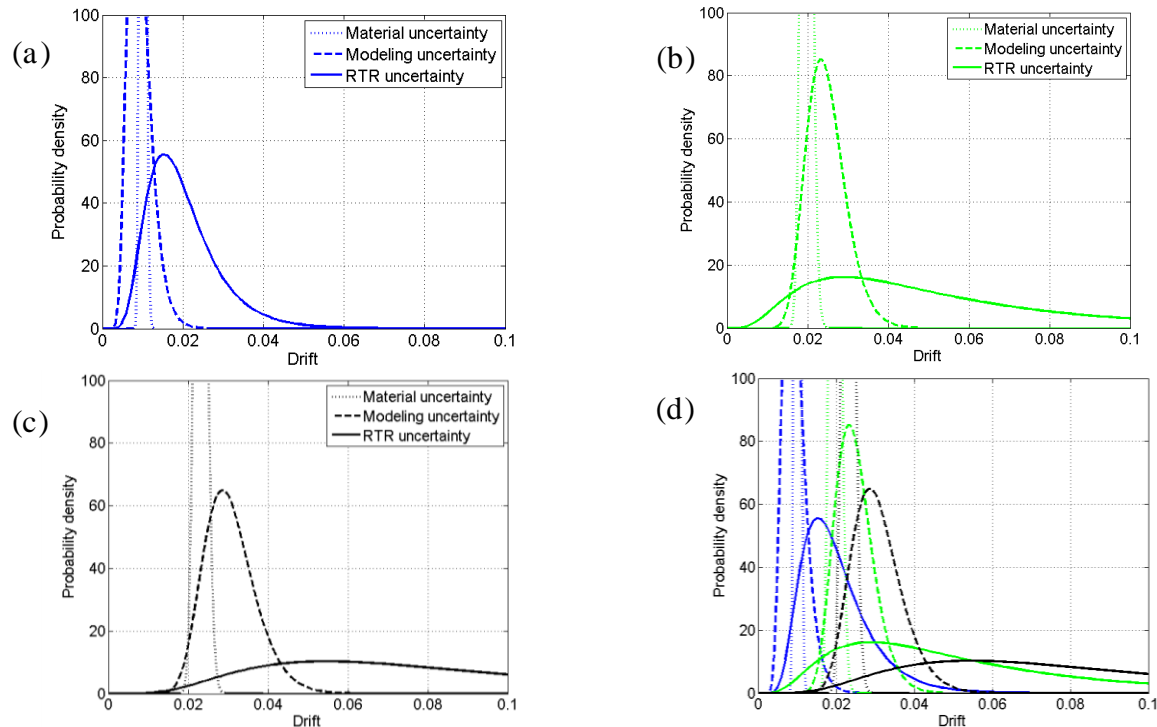


Figure 6. PDFs for drift of the steel column due to material, modeling, and RTR uncertainties at: (a)  $S_a(T_1) = 0.2$ , (b)  $S_a(T_1) = 0.35$ , (c)  $S_a(T_1) = 0.75$ , (d)  $S_a(T_1) = 0.2, 0.35, 0.75$  (g).

Table 1. Statistical parameters on the drift response of the selected column due to material, modeling, and RTR variabilities. [The results are presented in terms of natural logarithm of the drift values.]

Statistics	Sa(T <sub>1</sub> ) [g]	Source of Variability			Total Uncertainty (SRSS)
		Material	Modeling	RTR	
Mean Drift	0.20	0.010	0.009	0.020	N/A
	0.35	0.020	0.025	0.077	
	0.75	0.023	0.031	0.141	
Median Drift	0.20	0.010	0.009	0.018	
	0.35	0.020	0.024	0.052	
	0.75	0.023	0.030	0.131	
Standard Deviation of Drift Results	0.20	0.056	0.305	0.546	0.628
	0.35	0.061	0.197	0.888	0.912
	0.75	0.060	0.210	0.383	0.441

### Summary and Conclusions

This study quantifies the influences of material, modeling, and record-to-record (RTR) uncertainties on the drift response of steel beam-columns, and compares their influences relative to one another. Material uncertainty is quantified by conducting multiple dynamic analyses on a nonlinear model developed for a single steel beam-column, each time varying the input material properties generated based on data collected from coupon tests on ASTM A992 steel. The modeling uncertainty is quantified by developing multiple models in different software packages and different modeling resolutions for a single steel beam-column. The RTR uncertainty is computed using incremental dynamic analysis.

The influences of material, modeling, and RTR uncertainties on the predicted response of a steel beam-column is computed and compared against each other using a set of probability distribution functions representing the variation in the drift response of the column at multiple ground motion intensity levels. The results show that the record-to-record uncertainty accounts for the largest portion of the uncertainty in the predicted drift response in comparison with the material and modeling uncertainties. The analysis results also show that the representation of the uncertainty solely in terms of the standard deviation may lead to neglecting information related to quantification of uncertainty. The results show that the standard deviation of the lognormal distribution as a measure of the response uncertainty need to be used in conjunction with other statistical information such as number of simulations lead to collapse, to achieve a better understanding of the response distribution. Future studies should investigate the impact of each sources of uncertainty as well as the combination of various sources of uncertainty on the assessment of the system level response of structures.

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## References

- [1] A. Kazantzi, D. Vamvatsikos, and D. Lignos, "Seismic performance of a steel moment-resisting frame subject to strength and ductility uncertainty," *Eng. Struct.*, vol. 78, Jul. 2014.
- [2] C. B. Haselton and G. G. Deierlein, "Assessing Seismic Collapse Safety of Modern Reinforced Concrete Moment-Frame Buildings," PEER, University of California, Berkeley, PEER 2007/08, 2007.
- [3] B. Ellingwood, T. V. Galambos, J. G. MacGregor, and C. A. Cornell, "Development of a Probability-Based Load Criterion for American National Standard A58," Washington, 1980.
- [4] L. Ibarra, "Global Collapse of Frame Structures Under Seismic Excitations," Ph.D., Stanford University, 2003.
- [5] B. A. Bradley, "A critical examination of seismic response uncertainty analysis in earthquake engineering" *J. Earthq. Eng. Struct. Dyn.*, vol. 42, pp. 1717–1729, 2013.
- [6] S. Sattar, A. B. Liel, and P. Martinelli, "Quantification of Modeling Uncertainties Based on the Blind Prediction Contest Submissions," Structures Congress, pp. 1997–2008, 2013.
- [7] A. Elkady and D. Lignos, "Dynamic Stability of Deep and Slender Wide-Flange Steel Columns – Full Scale Experiments," in *Proceedings of the Annual Stability Conference Structural Stability Research Council*, Orlando, FL, 2016.
- [8] M. A. Hariri-Ardebili, S. Sattar, and H. E. Estekanchi, "Performance-based seismic assessment of steel frames using endurance time analysis," *Eng. Struct.*, vol. 69, no. Supplement C, pp. 216–234, Jun. 2014.
- [9] ASTM A992/A992M-11, "Standard Specification for Structural Steel Shapes," ASTM International, West Conshohocken, PA, 2015.
- [10] F. J. Massey, "The Kolmogorov-Smirnov Test for Goodness of Fit," *J. Am. Stat. Assoc.*, vol. 46, no. 253, pp. 68–78, Mar. 1951.
- [11] D. Vamvatsikos and C. A. Cornell, "Incremental dynamic analysis," *Earthq. Eng. Struct. Dyn.*, vol. 31, no. 3, pp. 491–514, 2002.
- [12] J. M. Weigand, "The Integrity of Steel Gravity Framing System Connections Subjected to Column Removal Loading," Thesis, 2014.
- [13] Pacific Earthquake Engineering Research Center (PEER), "OpenSees, Software," University of California, Berkeley, Berkeley, 2010.
- [14] ATC, "Guidelines for Nonlinear Structural Analysis for Design of Buildings Part I – General," Produced by the Applied Technology Council for the National Institute of Standards and Technology, NIST GCR 17-917-46v1, Redwood City, CA, 2017.
- [15] ASCE/SEI, "Seismic Rehabilitation of Existing Buildings (ASCE/SEI 41-13)," American Society of Civil Engineers, Reston, VA, 2013.
- [16] LS-DYNA R7.1. (2014), "LS-DYNA Keyword User's manual," Livermore Software Technology Corporation (LSTC), Livermore, California, 2014.
- [17] FEMA, "Quantification of Building Seismic Performance Factors (FEMA P695)," Applied Technology Council, Redwood City, CA, 2009.