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EVALUATION OF THE EFFECTS OF MODELING UNCERTAINTIES ON THE SEISMIC PERFORMANCE OF REINFORCED CONCRETE FRAMES

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ABSTRACT

In recent years, researchers have paid much attention to evaluate the effects of modeling parameters in steel frames; however this subject has been less studied in reinforced concrete (RC) frames. The modeling parameters are one of the important parts of the epistemic uncertainties in probabilistic assessment of structures that are obtained from physical and geometrical features of the structure; for example ASCE 41-13 (2014) introduces the parameters of nonlinear moment-rotation behavior of RC's beam column elements as a function of longitudinal and transverse reinforcement and also axial and shear demand. The modeling parameters are indeed the parameters obtained from backbone curves of the beam-column elements; which have been previously introduced by Ibarra et al. (2005) and include plastic rotation (θ_p), post capping rotation (θ_{pc}),post yield hardening stiffness(M_c / M_y) and etc. Evaluating the effects of these parameters can be executed by analyzing several RC frames under different values of the mentioned parameters. This study is aimed at evaluating the uncertainty effects in some of modeling parameters on the seismic performance of RC frames by using incremental dynamic analysis (IDA) and obtaining the collapse fragility curves of four frames with different story heights.

Moreover, the importance of proper correlation assumption between different modeling parameters, and also the performance level in which the assessment is executed will be discussed in this paper.

INTRODUCTION

In general, the uncertainties are categorized into two types, one of which is the uncertainty due to inherent randomness of natural phenomena and the other one is the uncertainty due to lack of human knowledge. The first mentioned category is often called as 'aleatory' and the second one is often called as'epistemic'uncertainty. Despite the aleatory uncertainty, the epistemic uncertainty can be reduced by more research that results in better understanding of the modeled phenomena. However, separating the source of uncertainty is not as practical as discussed at all cases. In seismic evaluation of structures the earthquake record specifications are assumed as aleatory and the other modeling and designvariables are assumed as epistemic uncertainties. Predicting the effects of uncertainties on the seismic performance of structures has been investigated by many researchers. Esteva and Ruiz (1989) studied seismic failure rates of multistory frames and concluded that the geometrical and mechanical properties of the frame's elements do not have a significant effect on the failure probability of structure. However many later studies obtained contrary results that emphasized on the importance of epistemic uncertainties. Vamvatsikos and Fragiadakis(2010) evaluated the sensitivity of modeling uncertainties on the seismic performance of a nine-story steel moment-resisting frame through incremental dynamic analysis (IDA) and concluded that the uncertainties in beam hinges has an important contribution in performance estimation. Zareian et al. (2010)considered the effects of epistemic source of variability in collapse capacity and combined them with aleatory uncertainties by using approximate methods such as ‘confidence level’ and ‘mean estimate’. Considering the effects of epistemic uncertainties has been developed to the extent that FEMA P695 (2009)discusses on these types of uncertainties and their effects on seismic evaluation.

This paper involves the assessment of the effects of uncertainties in three modeling parameters; consist of plastic rotation capacity, post capping rotation capacity and post yield hardening stiffness on the seismic performance of four reinforced concrete (RC) frames. The influence of structures height on the contribution level of modeling uncertainties is studied likewise. Furthermore, a number of researchers previously stated that the dependency of modeling parameter uncertainties on the seismic performance of structure highly depends on the performance level in which the structure is assessed. Ibarra and Krawinkler(2005) concluded that the modeling parameters have significant effect on the seismic response of deteriorating systems, especially when the structure experiences extreme seismic loads. Moreover, the correlation coefficient between the assumed random variables can increase the variability of structures response.These mentioned issues will also be briefly discussed in this paper

MODELING PARAMETERS

Performance-based earthquake engineering needs an analytical model that can predict the structural seismic performance. Modeling parameters are indeed the parameters obtained from the tri-linear backbone curves of the beam-column elements; which have been previously introduced as lumped-plasticity model by Ibarra et al. (2005) .These parameters introduce the moment-rotation behavior as a function of geometrical and mechanical characteristics of the beam-column elements; for example ASCE 41-13 (2014) introduces the parameters of nonlinear moment-rotation behavior of RC’s beam-column elements as a function of longitudinal and transverse reinforcement and also axial and shear demand.

The remarkable specification of this model is the ability of considering the post-capping negative stiffness which is necessary to simulate the collapse of RC structures. Accurate modeling of this part along with other parts of the mentioned backbone curve can play a key role to predict the seismic performance of the structure such as collapse.

The modeling parameters to consider both monotonic and cyclic behavior of the element consist of yielding moment (M_y), effective stiffness (EI_{eff}), plastic rotation ($^{-}{}_{p}$), post-capping rotation ($^{-}{}_{pc}$), post yield hardening stiffness (M_c / M_y) and cyclic energy dissipation capacity (ª). Some of the modeling parameters are illustrated in Fig. 1.

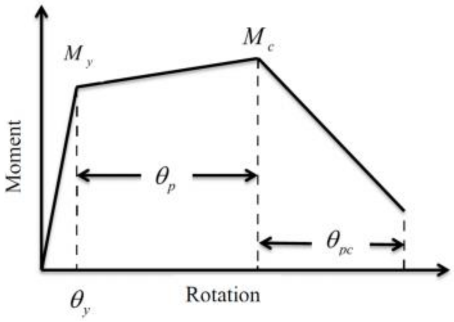

Figure 1. The backbone moment-rotation curve and a number of modeling parameters

PREDICTIVEEQUATIONS

Haselton et al.(2007) calibrated the modeling parameters as predictive equations from 255 RC column experimental tests. Likewise, Eurocode 8 - part3(2005) represents structurally similar equations to predict the modeling parameter values. Table 1introduces Haselton’s calibrated equations to predict the mean values of a number of the modeling parameters which are assessed in this study. Table 1 contains the reported logarithmic standard deviations for each calibration equation. Additional information about modeling parameters and predictive equations can be found in Haselton et al.(2007).

Table 1. Predictive equations and related logarithmic standard deviations for three modeling parameters

Parameter	Predictive equation		Logarithmic standard deviation
Plastic rotation	$\bar{\ }_{p} = 0.13(1+0.55a_{sl})(0.13)^{\neg}(0.02+40\,°_{sh})^{0.65}(0.57)^{0.01f_c'}$	(1)	0.62
Post cap rotation	$\bar{\ }_{pc} = (0.76)(0.031)^{\neg}(0.02+40\,°_{sh})^{1.02} \leq 0.10$	(2)	0.72
Post yield hardening stiffness	$M_c / M_y = (1.25)(0.89)^{\neg}(0.91)^{0.01f_c'}$	(3)	0.1

Where¬ is the axial load ratio, $°_{sh}$ is the area ratio of transversal reinforcement, a_{sl} is an indicator to signify possibility of longitudinal rebar slip to pass the column end and f_c' is concrete’s compressive strength

MODELING PROCEDURE

In order to evaluate the effects of modeling parameter on the seismic performance of structures, fourRC frames which have 1, 2, 4 and 8 number of stories are designed according to latest design provisions. In the next stepthe modeling parameters for each beam-column element of the mentioned frames, were obtained from the represented equations in Table 1. Theseacquired values are then implemented in the assessment model and IDA analysis has been executed by OpenSees software (2005). Earthquake records, which are used for IDA analysis are in accordance with Vamvatsikos (2002). The four story frame’s design information is demonstrated in Fig. 2., Table 2 and Table 3 as the representative of studied frames; Therefore similar information of other frames are omitted due to lack of space.

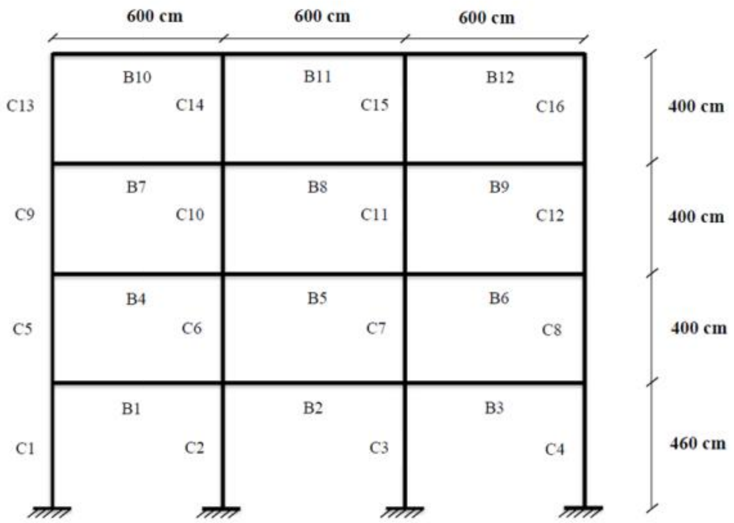

Figure 2. The four story frame’s information

RESULTS AND DISCUSSION

The uncertainty effects of plastic rotation, post-capping rotation and post yield hardening stiffness on the performance of four mentioned frames, was evaluated by perturbing each modeling parameter to « –± value separately; and the results of IDA analysis were obtained in each step. Before representing the results, it should be mentioned that in the « case all parameters are set to mean values and in next case the value of related parameter is perturbed due to considered standard deviation. Fig. 3. shows the capacity curves of the four-story frame in different cases of study, at each the uncertainty of a modeling parameter is considered in the model. Figure 3 indicates that the plastic rotation has the most effect on the capacity curve between the examined parameters. Post capping rotation and post yield hardening stiffness have the next levels of significance, respectively.

Table 2. Column section documentation of the four story frame

	h(cm)	b(cm)	ν	ρ_{tot}	ρ_{sh}
C1	55	55	0.06	0.0130	0.0070
C2	55	55	0.13	0.0163	0.0070
C3	55	55	0.13	0.0163	0.0070
C4	55	55	0.06	0.0130	0.0070
C5	55	55	0.05	0.0130	0.0070
C6	55	55	0.10	0.0163	0.0070
C7	55	55	0.10	0.0163	0.0070
C8	55	55	0.05	0.0130	0.0070
C9	55	55	0.03	0.0113	0.0070
C10	55	55	0.06	0.0145	0.0070
C11	55	55	0.06	0.0145	0.0070
C12	55	55	0.03	0.0113	0.0070
C13	55	55	0.02	0.0113	0.0070
C14	55	55	0.03	0.0145	0.0070
C15	55	55	0.03	0.0145	0.0070
C16	55	55	0.06	0.0113	0.0070

Table 3. Beam section documentation of the four story frame

	h(cm)	b(cm)	ρ	ρ´	ρ_{sh}
B1	60	55	0.0043	0.0083	0.0033
B2	60	55	0.0043	0.0083	0.0033
B3	60	55	0.0043	0.0083	0.0033
B4	60	55	0.0037	0.0075	0.0033
B5	60	55	0.0037	0.0075	0.0033
B6	60	55	0.0037	0.0075	0.0033
B7	60	55	0.0032	0.0060	0.0033
B8	60	55	0.0032	0.0060	0.0033
B9	60	55	0.0032	0.0060	0.0033
B10	60	55	0.0032	0.0045	0.0033
B11	60	55	0.0032	0.0045	0.0033
B12	60	55	0.0032	0.0045	0.0033

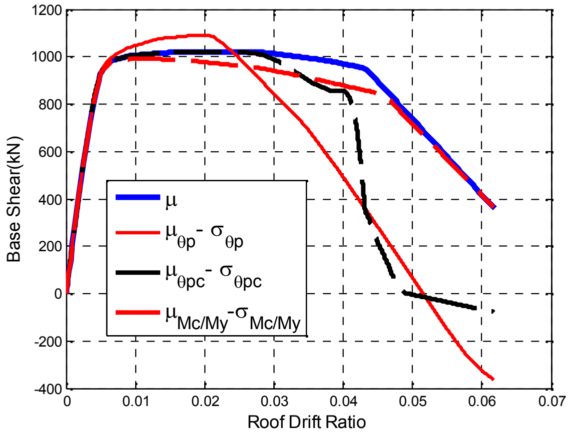

Figure 3. Effects of modeling parameters uncertainty on the capacity curves of four story frame

Fig. 4. represents the IDA results of the 4-story frame. Similar to capacity curves,Plastic rotation has the most effect on the IDA curves of all examined frames.It should be mentioned that the effect of plastic rotation’s uncertainty on the IDA curve is only shown in Figure 4 and the other results are omitted with the aim of clarity.With respect to the IDA results and with the lognormal distribution assumption of spectral acceleration values at each performance level, Figures 5 shows the fragility curves of the four studied frames at global instability (GI) performance level which is corresponding to 10% maximum inter-story drift. It should be noted that the spectral accelerations at each performance level can be distributed differently, although it is not in the scope of this study; additional information can be found at Eads et al. (2013).As it was expected, the plastic rotation has the greatest impact on the fragility curves of allinvestigated frames.

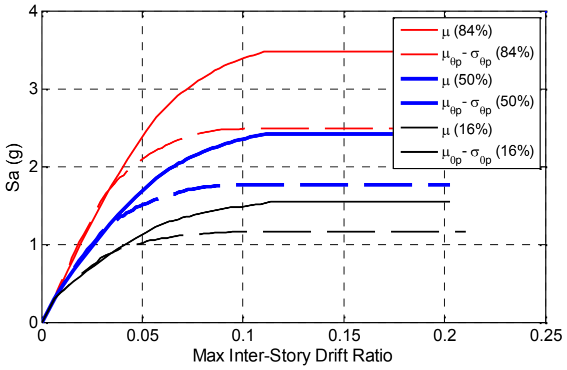

Figure 4. Effect of plastic rotations uncertainty on the summarized IDA curves of four story frame

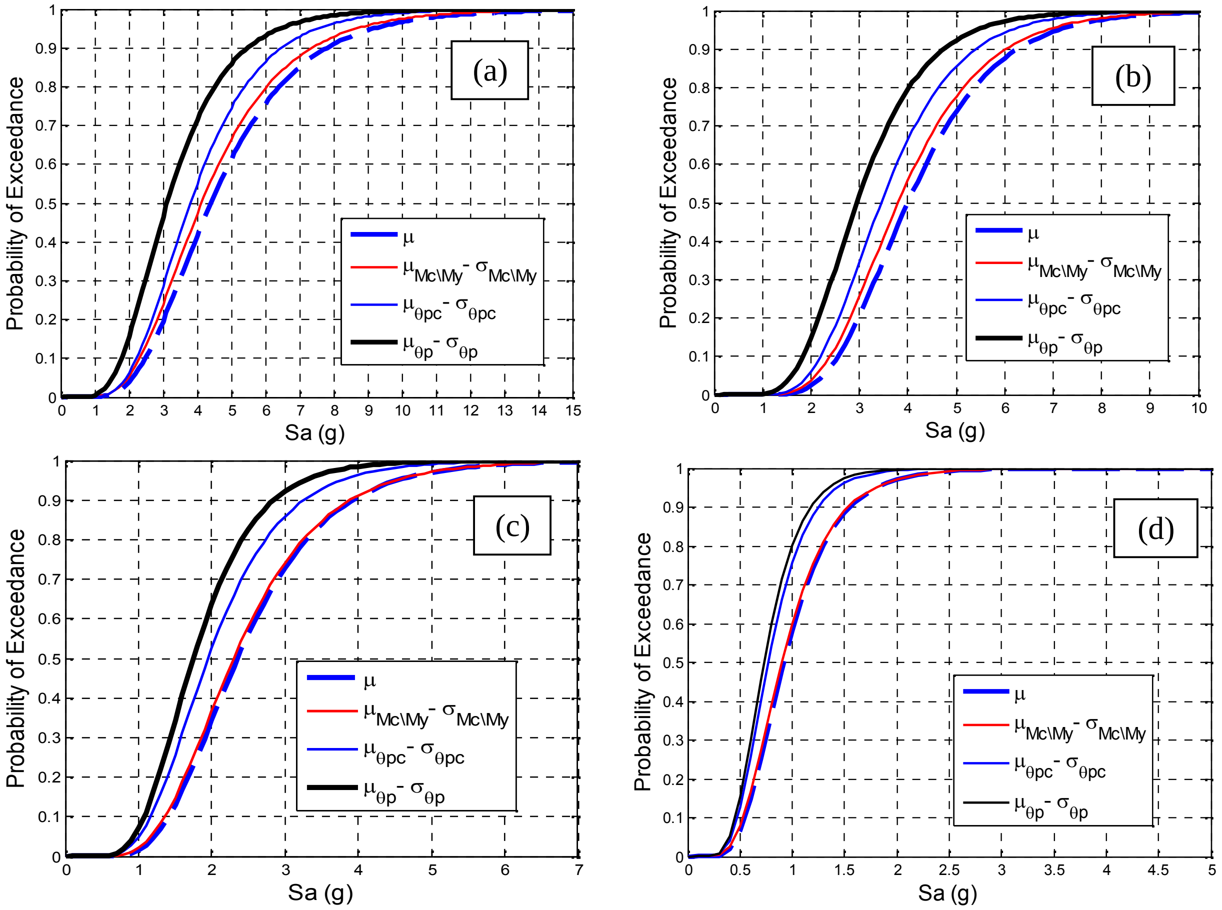

Figure 5. Effect of uncertainty in modeling parameters on the fragility curves of fourstudied frames
(a) One story (b) Two story (c) Four story (d) Eight story

Table 4 compares the median collapse capacity variations of the four investigated frames. Each value in Table 4 represents the ratio of difference between the median collapse capacity of base case and the median collapse capacity of the related uncertain case. The variations in Table 4 indicate a contrariwise trend between the number of stories and the effectiveness of post yield hardening stiffness and plastic rotation's uncertainty, on the fragility curve of studied frames. Post-capping rotation has not as recognizable trend as the other two parameters, but there is an approximately similar trend between theeffectiveness of post-capping rotation's uncertainty and the number of stories.

Table 4. Variation of the median collapse capacity from base case to related uncertain case

Number of stories	$—_{p}$	$—_{pc}$	M_c / M_y
1	29.09 %	13.64%	6.13%
2	26.25%	13.75%	5%
4	25.53%	17.02%	2.55%
8	20.65%	16.3%	2.17%

Table 5. Logarithmic standard deviations corresponding to considering or non-considering modeling uncertainties

Number of stories	$\pm_{base}$	$\pm_{total}$	$\frac{\pm_{base} - \pm_{total}}{\pm_{base}}$
1	0.45	0.58	28.9%
2	0.35	0.48	37.1%
4	0.41	0.54	31.7%
8	0.41	0.50	21.9%

First Order Reliability Method (FOSM) is used to combine the uncertainty of modeling parameters. By this method, the median collapse capacity remains as the median collapse capacity of the base case and the combined standard deviation is computed as Eq(4).

$$\pm_{total}^{2} = [\sum_{i=1}^{n}\sum_{j=1}^{n}(\frac{\partial g}{\partial x_i} \times \frac{\partial g}{\partial x_j})_{x=«} \times °_{ij} \times \pm_i \times \pm_j] + \pm_{base}^{2} \tag{4}$$

Collapse fragility curves in cases of considering or non-considering the total uncertainty of modeling parameters are shown in Figure 6 and the corresponding standard deviations are represented in Table 5. Considering the uncertainty of modeling parameters increases the variability of collapse capacity at all four studied frames. However there is not a logical trend between the ratio of standard deviation's increase and the number of stories.

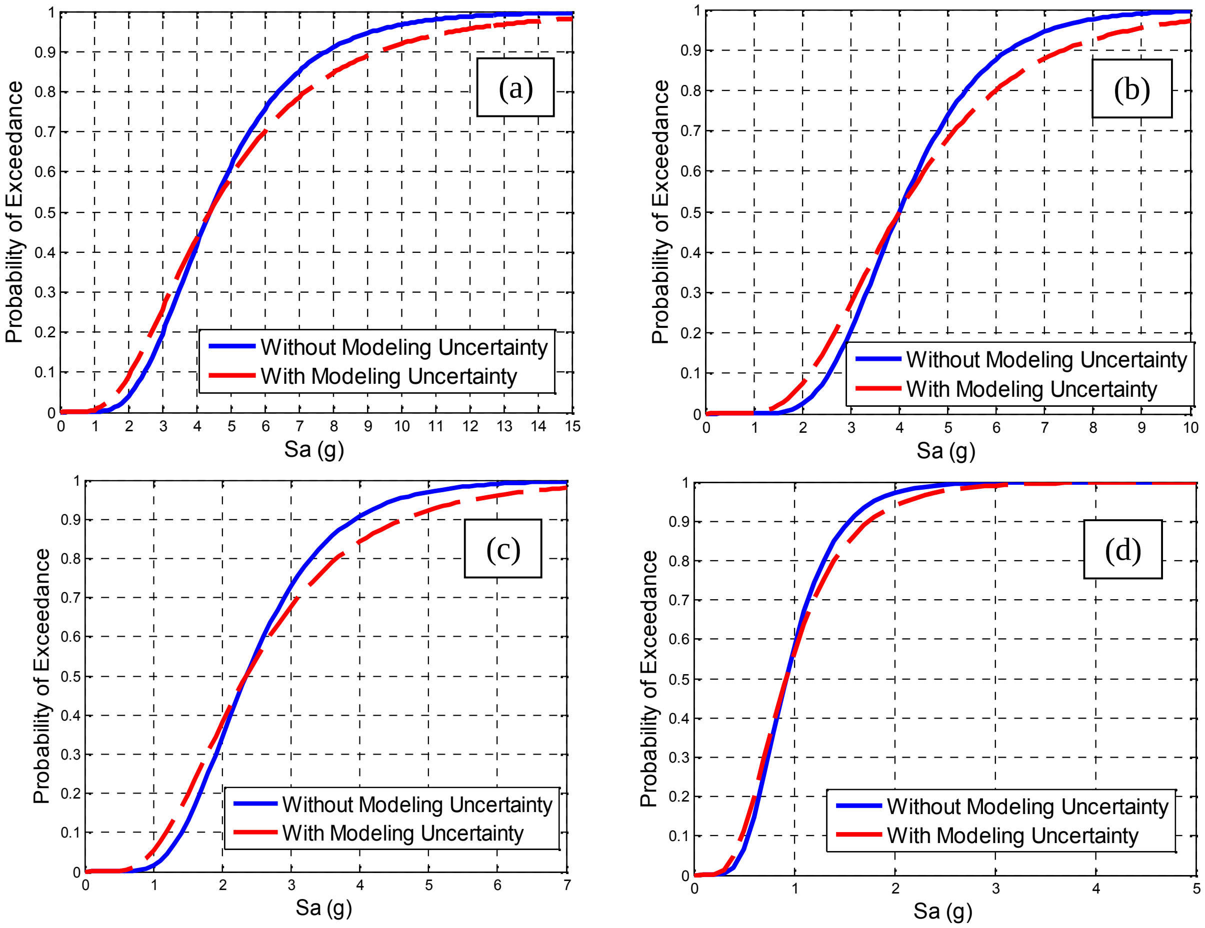

Figure 6. Comparing the fragility curves of four studied frames in cases of considering and non-considering the total uncertainty of modeling parameters

(a) One story (b) Two story (c) Four story (d) Eight story

Fig. 7. illustrates that there is not a considerable change in the fragility curve of one story frame, which had the most level of difference between CP and GI performance levels; this proves the fact that the uncertainty of modeling parameters are important, only if the structure experiences extreme seismic loads.

Correlation of random variables can impact the result of seismic performance. Figure 8 shows the effect of correlation between plastic rotation and post-capping rotation, which is the most probable case for correlation assessment, on the fragility curve of one story frame. Two extreme cases of correlation between the mentioned parameters are compared in Figure 8. By using the FOSM method to combine the uncertainties there is not a remarkable change in collapse fragility curves.

CONCLUSIONS

This paper evaluated the uncertainty of modeling parameters on the collapse probability of four RC frames, which had 1, 2, 4 and 8 numbers of stories. With respect to the results of IDA, it was proved that plastic rotation, post capping rotation and post yield hardening stiffness, relatively had the most impact on collapse fragility curves of all investigated frames. For instance, decreasing the values of plastic rotation, post capping rotation and post yield hardening stiffness, causes a29.09%, 13.64% and 6.13% decrease in median collapse capacity of one story frame, respectively. The importance order of the mentioned parameters was also demonstrated by the results of push over analysis.

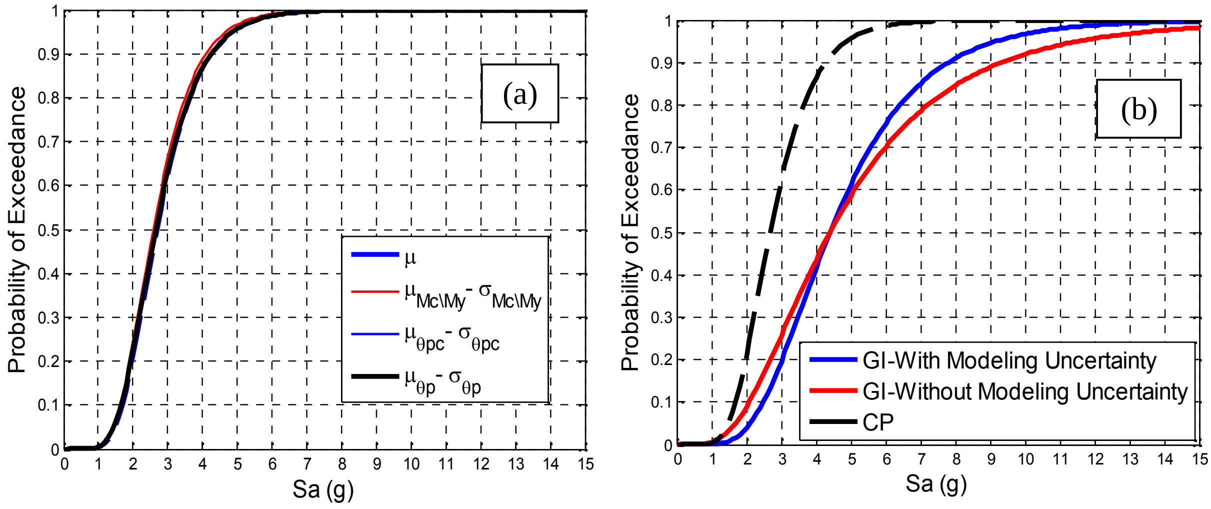

Figure 7. Comparing the effect of modeling uncertainties on CP and GI performance levels, at one story frame
(a) Effect of each modeling parameter separately at CP
(b) Combination of modeling uncertainties

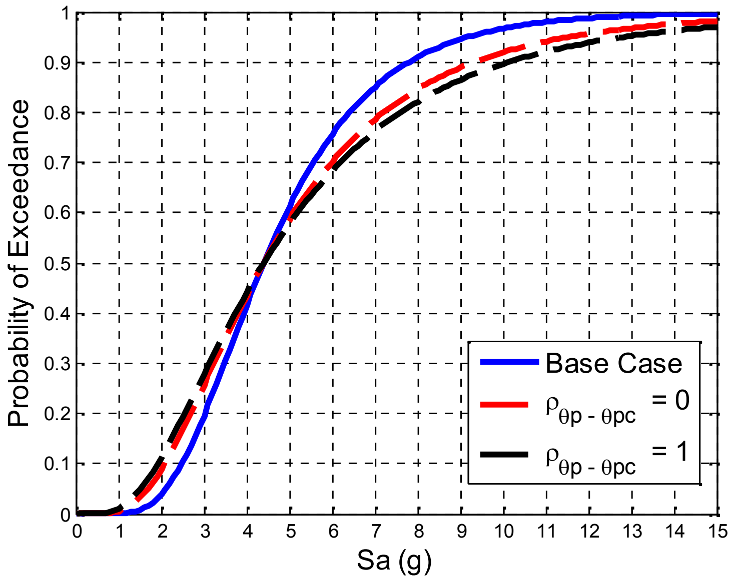

Figure 8. Effect of correlation between plastic and post capping rotation on the fragility curve of one story frame

Considering the effect of total studied modeling parameters, and combining them by the FOSM has a significant effect on the collapse distribution function, as it causes a 28.9% increase in the logarithmic standard deviation of one story frame's collapse probability distribution function. However using the FOSM method to combine the uncertainty effects might not be always an efficient method, since it linearly approximates the structure's response and does not change the median collapse capacity in addition to not efficiently showing the correlation effects; hence using another methods to combine the uncertainty effects may develop the results in future research.

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