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Adequacy of Linear Viscous Damping Models for Nonlinear Response History Analysis

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Abstract

Damping forces appear to be unrealistically large if linear viscous damping, traditionally used to model energy dissipation during pre-yield motions, is also used in nonlinear response history analysis (RHA) of buildings. Some researchers have recommended that a limit should be imposed on the magnitude of the damping forces, resulting in a nonlinear viscous damping model; such a model can be difficult to implement in commercial computer codes. Presented in this paper are results of nonlinear RHA of the 20-story SAC-Los Angeles building subjected to 11 ground motions (GMs) corresponding to earthquake events with 2% probability of exceedance in 50 years. Interpretation of these results leads to the conclusion that linear viscous damping models are adequate for estimating seismic demands due to MCE_R design-level GMs.

Keywords: Buildings; viscous damping; seismic-demand;, bounded-damping, nonlinear response history analysis.

1. Introduction

Researchers have demonstrated that damping forces appear to be unrealistically large if linear viscous damping, commonly used to model energy dissipation during pre-yield motions, is also used in nonlinear response history analysis (RHA) of buildings [1, 2, 3, 4, 5, 6, 7] of buildings. This problem arises because yielding of structural elements limits their resisting forces, but no such mechanism exists for limiting the damping forces. They can increase without limit in proportion to velocities, which may become large because of yielding, especially as the structure approaches a state of collapse.

If damping forces are overestimated, the seismic demands on the building will obviously be underestimated. Therefore, researchers have presented several proposals to control the damping forces [5, 8, 9, 10]. One of the proposals [4] imposes an upper bound on the damping forces, resulting in a nonlinear viscous damping model; such a model may be difficult to implement in commercial computer codes.

In this paper, we investigate whether building response to design-level ground motions (2% probability of exceedance in 50 years or return period of 2475 years) can be estimated satisfactorily or a bounded damping model is necessary.

2. Damping Models

The damping models considered include two linear viscous damping models: Rayleigh damping and constant modal damping. In the latter model, the damping matrix is defined as the superposition of modal damping matrices [11] with constant (or equal) damping ratios specified in all modes. The third model is a nonlinear viscous damping model with interstory dampers with a bound (or a limit imposed on the damping forces). The limit imposed on the damping force in a story is 2ζ times the strength of the story [4]. Detailed presentation of the model is available in Qian et al. [12].

3. Structural Systems

The building analyzed is the 20-story steel moment-resisting frame that was designed as part of the SAC project for post-Northridge earthquake design criteria in Los Angeles area [13, 14]. The dimensions and section sizes were taken from Appendix B of the FEMA-356 SAC Steel Report [15]. The subterranean part of the building was ignored and the columns were fully constrained at the base.

A simple model of the perimeter frames of the building was based on centerline dimensions; beams were modeled between centerlines of columns without rigid offsets, panel zones, or top and bottom cover plates. The fundamental period of vibration is 3.81 sec for the 20-story model. Damping ratios for all damping models were assumed to be 2%. This is generally consistent with values estimated from motions of tall buildings recorded during earthquakes [16]. It also conforms to values recommended in design guidelines [17]. Details of the building model are available in Qian et al. [12].

4. Ground Motions

Ground motions were selected for the Los Angeles City Hall site, the assumed location for the building, for earthquake events with 2% probability of exceedance (PE) in 50 years (i.e., return period of 2475 years). This corresponds to the MCE_R event defined in design codes and guidelines. Consistent with professional practice, the target spectrum was defined as the Conditional Mean Spectrum (CMS) [18]. The CMS is constructed for a selected value of the conditioning period T^*, where the spectral acceleration is specified. As is common, T^* was selected as T_1, the fundamental vibration of the building, and $A(T^*)$ as the value that matches the Uniform Hazard Spectrum (UHS).

Shown in Fig. 1 is the UHS for the selected site, and the CMS conditioned on T^* = 3.81 sec, the fundamental vibration period T_1 of the simple model of the 20-story frame. The spectral value $A(T^*)$ = 0.195g. Also included are the response spectra of the 11 GMs scaled to this $A(T^*)$ and selected for close agreement with the CMS in shape.

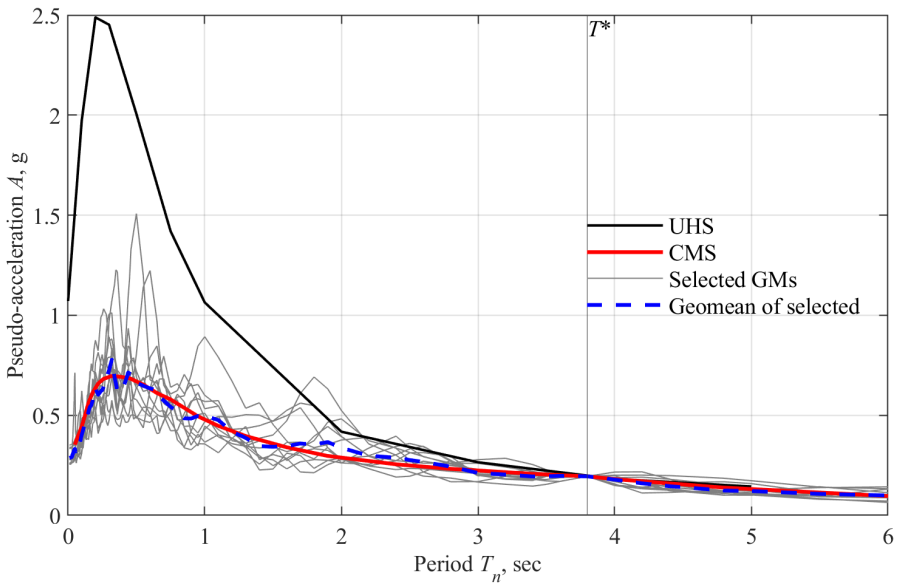

Fig. 1 – Uniform hazard spectra (UHS), Conditional Mean spectrum (CMS), and response spectra for 11 scaled grounds (GMs) selected for similarity to the CMS.

5. Structural Response

Nonlinear RHAs of the building model subjected to the set of 11 GMs were implemented in OpenSees [19, 20] for three different damping models. Presented in Fig. 2 and Table 1(a) are the average (over 11 GMs) values of peak floor displacements, peak story drifts, and peak plastic rotations of the beam hinges; these structural responses are essentially identical for the two linear viscous damping models but both underestimate the demands relative to the bounded damping model by less than 11%; see Table 2(a). The response of the structure to the GM RSN1188, which imposes the largest demands among the 11 GMs, is plotted in the same format in Fig. 4; in addition, the variation of roof displacement with time is presented in Fig. 3. Observe that the response is, essentially, identical among the three damping models for the first 100 sec of the GM, but thereafter the results begin to diverge; see Fig. 3. For this GM of very long duration, the peak demands occur near the end of the excitation. Interstory drifts and plastic rotations, both approximately 6%, are significantly larger than the 4.5% allowed by design guidelines [17, 21]. At these large inelastic deformations, the constant modal damping model underestimates seismic demands by 18–21% relative to the bounded damping model; greater underestimation of 23–26% is observed for the Rayleigh damping model; see Table 2(a).

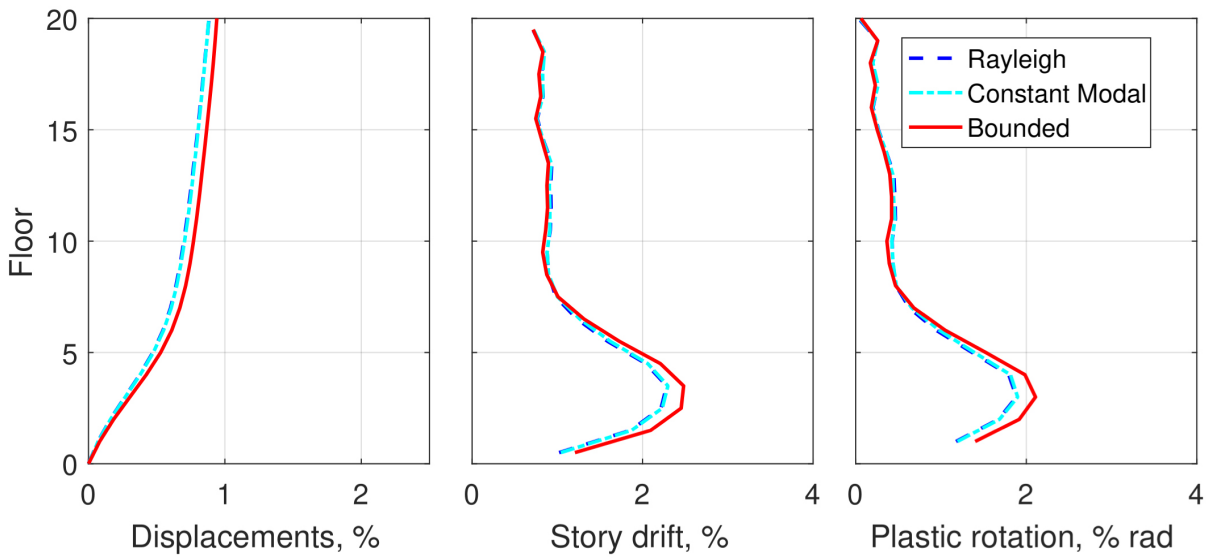

Fig. 2 – Average (over 11 GMs) seismic demands on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; 2% damping: (a) peak floor displacements; (b) peak story drifts; and (c) peak plastic rotations.

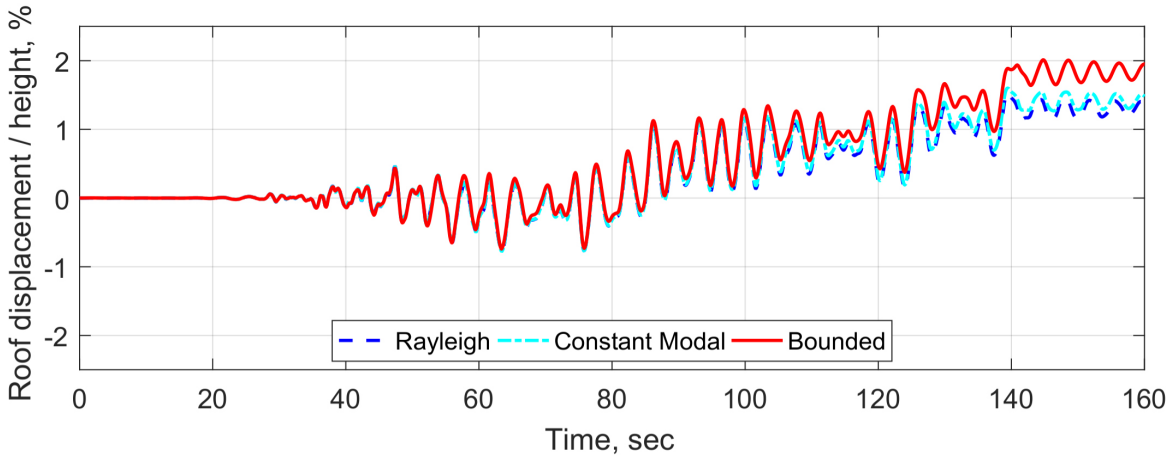

Fig. 3 – Response history of roof displacement of the 20-story frame for three damping models subjected to RSN1188 GM scaled corresponding to 2% PE in 50 years; 2% damping.

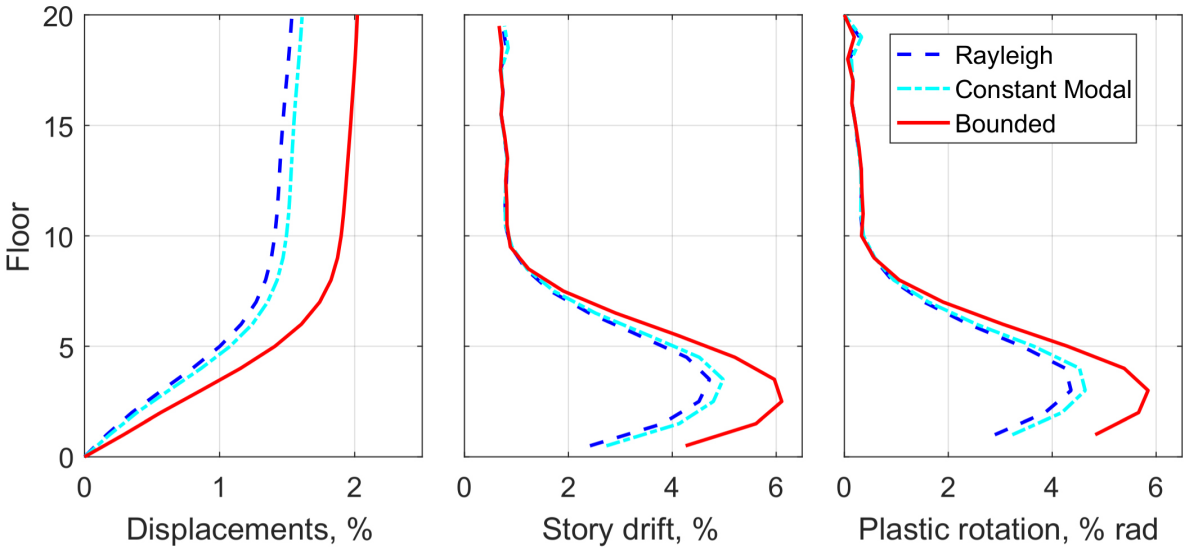

Fig. 4 – Maximum (over 11 GMs) seismic demands on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; 2% damping: (a) peak floor displacements; (b) peak story drifts; and (c) peak plastic rotations.

Table 1 – Seismic demands on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; damping = 2% and 5%.

Damping Model	(a) 2% damping				(b) 5% damping			
	Avg of 11 GMs		Max over 11 GMs		Avg of 11 GMs		Max over 11 GMs	
	Story drift %	Plastic rotations, % radians	Story Drift, %	Plastic rotations % radians	Story drift %	Plastic rotations, % radians	Story drift %	Plastic rotations, % radians
Rayleigh	2.28	1.88	4.72	4.36	2.01	1.54	3.88	3.50
Constant modal	2.30	1.90	4.98	4.64	2.04	1.63	4.22	3.85
Bounded	2.48	2.11	6.11	5.85	2.13	1.73	4.44	4.02

Table 2 – Underestimate (%) of seismic demands on the 20-story frame by linear viscous damping models relative to bounded damping subjected to GMs with 2% PE in 50 years; damping = 2% and 5%.

Damping Model	(a) 2% damping				(b) 5% damping			
	Avg of 11 GMs		Max over 11 GMs		Avg of 11 GMs		Max over 11 GMs	
	Story drift	Plastic rotations	Story drift	Plastic rotations	Story drift	Plastic rotations	Story drift	Plastic rotations
Rayleigh	8.1	10.9	22.8	25.4	5.6	11.0	12.5	13.0
Constant modal	7.3	10.0	18.5	20.7	4.2	5.8	4.9	4.2

Presented in Fig. 5 are the height-wise distributions of peak story shears, V_s, and story damping forces, V_d, normalized relative to the total weight of the building and the ratio V_d / V_s. Because all stories of the building yielded, the V_s/W plot is the same for all damping models; it is simply the height-wise distribution of the story strengths. The ratio V_d / V_s is close to 4%, the limit of 2ζ imposed in the bounded damping model, but this ratio reaches approximately 8%—approximately doubled the 2ζ limit—for the linear damping models. Note that although larger than 2ζ; this ratio is nowhere close to the alarming value of 60% reported for a shear building [4], even though story drifts and plastic rotations are quite large: approximately 6%.

Although 2% damping assumed in the preceding example is generally consistent with measured values for tall steel buildings [16] and recommended values [17], we examine if the preceding observations would remain valid if damping were 5%, a value that had been commonly assumed for several decades. Larger damping tends to increase damping forces, which would suggest larger differences between structural responses with linear and bounded damping models. However, it also reduces the response, implying less yielding, which would suggest smaller differences between the two responses; after all, linear and bounded damping models would give essentially identical response in the absence of yielding of the structure.

To explore the overall effect of the two competing factors, nonlinear RHAs of the 20-story frame with 5% damping subjected to the same 11 GMs were repeated. The average responses are shown in Figs. 6 and the maximum demands (over 11 GMs) in Fig. 8; in addition, the variation of roof displacement with time is presented in Fig. 7. The story drifts and plastic rotations are now reduced, and the constant modal damping model is able to closely follow the roof displacement history determined using the bounded damping model during the entire 160 sec duration of the GM; see Fig. 7. For this GM, the constant modal damping model predicts peak demands within 5% of those from the bounded damping model; in contrast, the Rayleigh

damping model underestimates demands by 13%; see Table 2(b). At average (over 11 GMs) plastic rotations less than 2% rad [Table 1(b)], the linear damping models underestimate seismic demands to a lesser degree: 4–6% for constant modal damping and 6–11% for Rayleigh damping; see Table 2(b).

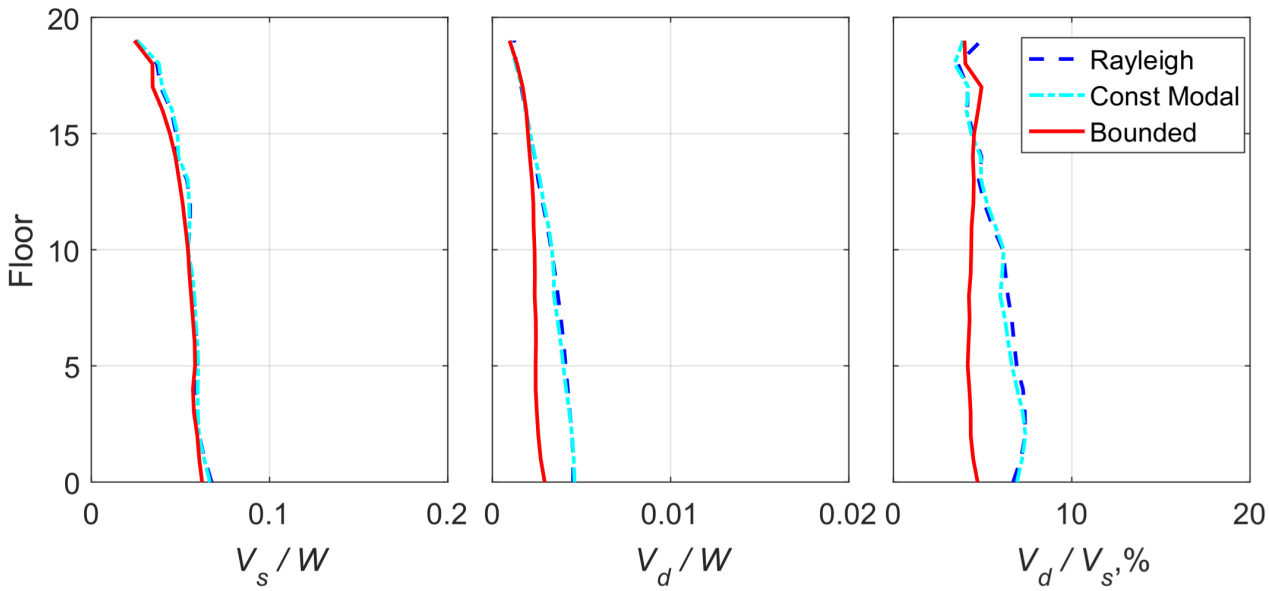

Fig. 5 – Maximum (over 11 GMs) story forces on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; 2% damping: (a) peak shear force V_s; (b) peak damping force V_d; and (c) ratio of V_d/V_s.

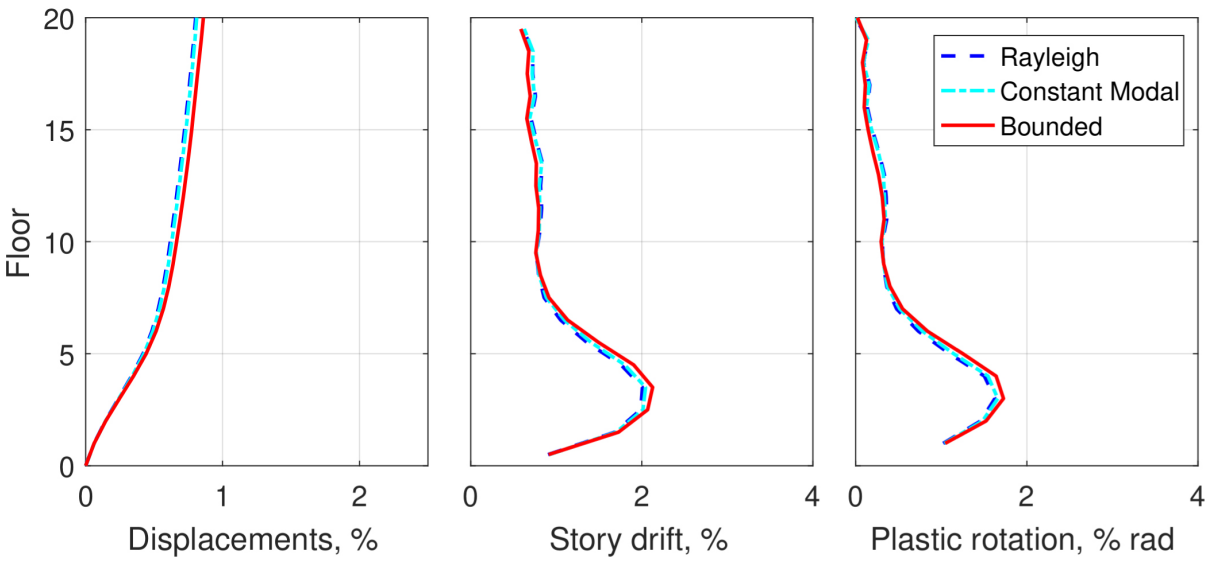

Fig. 6 – Average (over 11 GMs) seismic demands on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; 5% damping: (a) peak floor displacements; (b) peak story drifts; and (c) peak plastic rotations.

Compared to Rayleigh damping, the constant modal damping model consistently predicts seismic demands closer to the bounded damping model. Rayleigh damping implies much higher damping in the higher modes of vibration compared to the latter model, thus underestimating the seismic demands to a greater degree; see Table 2.

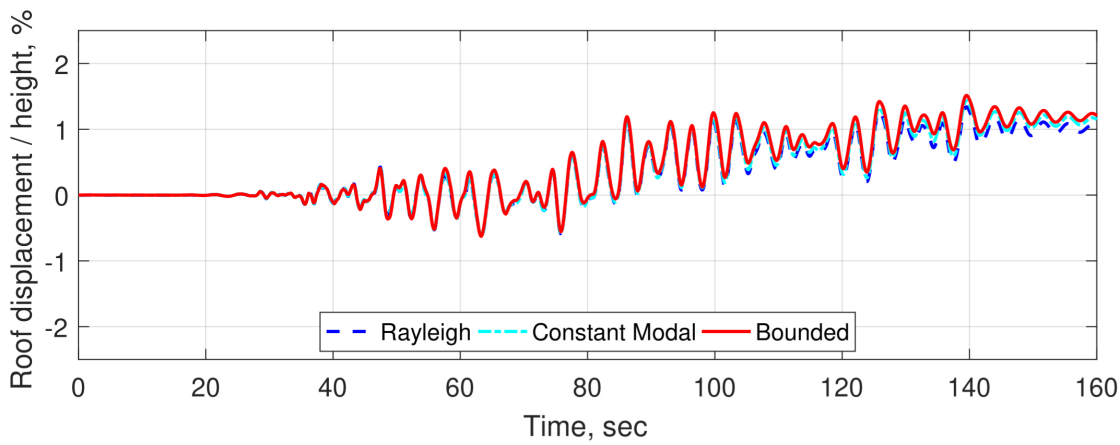

Fig. 7 – Response history of roof displacement of the 20-story frame for three damping models subjected to RSN1188 GM scaled corresponding to 2% PE in 50 years; 5% damping.

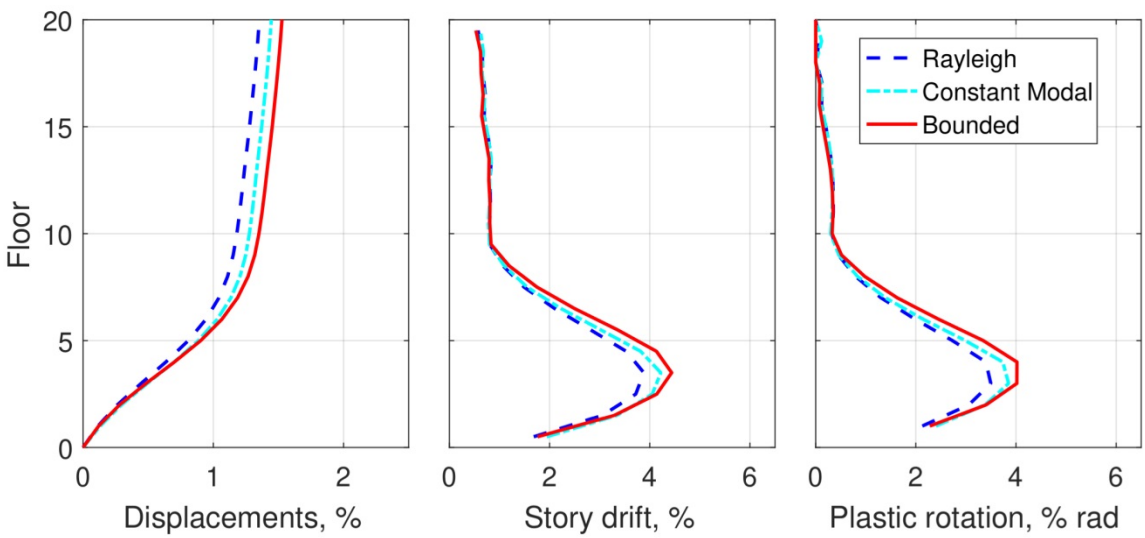

Fig. 8 – Maximum (over 11 GMs) seismic demands on the 20-story frame for three damping models due to GMs with 2% PE in 50 years; 5% damping: (a) peak floor displacements; (b) peak story drifts; and (c) peak plastic rotations.

6. Conclusions

Results of nonlinear RHA of a simple model of the 20-story SAC building subjected to 11 GMs consistent with the seismic hazard corresponding to 2% probability of exceedance in 50 years (return period of 2475 years) have demonstrated that the linear damping models considered here, Rayleigh damping and constant

modal damping, are adequate for estimating seismic demands for MCE_R-level GMs. Between these two linear models, constant modal damping is preferable because it leads to larger demands that are closer to those obtained using the bounded damping model. These results indicate that at MCE_R-level GMs, the building satisfies the limits on average story drifts and plastic rotations specified in design guidelines. Bounding the damping forces—such that V_d/V_s does not exceed 2ζ—does not increase the seismic demands significantly enough to reach a contradictory conclusion.

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