



Force Limiting Connections to Mitigate Accelerations in Moment Resisting Frames with Pinned-Base Spines

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Abstract. Mid-rise moment resisting frames (MRF) which utilize supplemental pinned-base spines (spine) to prevent the formation of story mechanisms experience higher mode accelerations at near elastic spectral values. Force Limiting Connections (FLC) can be introduced to reduce the floor accelerations from the higher mode responses while having small impact on first-mode response and maintaining the story mechanism prevention from the spine. Results from nonlinear response history analysis (NRHA) of a 4-story MRF-Spine system show how floor accelerations for higher modes are reduced with the addition of FLC placed between the MRF and spine. Peak effective pseudo accelerations are utilized to show how pseudo spectral accelerations are reduced by the introduction of FLC. Full-scale testing of the 4-story MRF-Spine structure supports the numerical results of the MRF-Spine and MRF-Spine-FLC numerical analyses. These results show the potential benefits of adding FLC to MRF-Spine systems.

Keywords: steel moment-resisting frames · spine · nonlinear response history analysis · story mechanisms · acceleration control

1 Introduction and Concept

Conventional ductile steel moment resisting frame (MRF) systems for mid-rise buildings are prone to earthquake damage and tend to concentrate lateral drift in single stories, increasing the risk of collapse by story mechanism (soft story) [4, 6, 7, 19]. Past work shows that MRF seismic response can be improved by combining the MRF with a “spine,” which is a stiff elastic pinned-base supplemental element that runs continuously along the height of the MRF. The spine mitigates concentrated lateral drift and single-story

yield mechanisms resulting from concentrated plasticity in the MRF columns [12, 15, 18]. However, systems with supplemental spines develop large seismic forces and floor accelerations associated with higher-mode responses due to the elimination of these undesirable single-story yield mechanisms [11, 14]. The increased accelerations raise the potential for damage to acceleration-sensitive building components. Recent research on integrating deformable force-limiting connections (FLC) within frame-spine systems indicates that FLC can reduce seismic forces and floor accelerations, thereby decreasing the likelihood of damage to acceleration-sensitive equipment [17].

The implementation of FLC improves the behavior of MRF-Spine systems by controlling total floor accelerations while continuing to prevent single-story yield mechanisms. Previous research on utilizing FLC between gravity resisting systems (GRS) and lateral force resisting systems (LFRS) hints at the benefits of FLC in reducing floor accelerations within an MRF-Spine system as well [17]. The FLC utilized in this research introduce flexibility into the MRF-Spine system, and limit the MRF-Spine connection forces through yielding of the FLC. The goal of this research is to show how capping the transfer of forces (i.e. force-capping behavior) from the MRF to the spine can reduce total floor accelerations in MRF-Spine systems.

An opportunity to perform full-scale testing of the MRF-Spine-FLC system, based on a 4-story MRF, at E-Defense in 2020 provided a test bed for evaluating potential FLC designs. Unlike previous research on FLC which looked at fully decoupling a lateral force resisting system (LFRS) from the gravity system supporting the mass [17], this research adds FLC between a spine and an LFRS which also supports the mass. In this configuration, designing the FLC to reduce higher mode accelerations is more of a challenge due to coupling effects between all modes. Peak effective pseudo accelerations are utilized to judge the effectiveness of potential FLC designs. Nonlinear response history analysis (NRHA) is also employed to estimate the effect of FLC on the MRF-Spine system.

2 Overview of Experimental Test Specimen

An existing full-scale 3-story MRF test specimen was made available to our research team for the purpose of experimental tests on the MRF-Spine-FLC system concept [8, 9]. The experiments included testing with MRF-Spine connections that were nearly rigid as a baseline for comparison with the MRF-Spine-FLC system. Because the MRF-Spine-FLC system is targeted for mid-rise MRFs (between 4 and 12 stories) alterations were made to the existing 3-story MRF to better match the modal properties of US-designed mid-rise SMFs. An additional story was added to give the test specimen four total stories. Additional weight was added to the third and fourth floors to elongate the modal periods. Finally, to create the potential story-mechanism response of some US-designed SMFs, the column bases were changed from fixed to pinned to force a story-mechanism in the MRF alone (i.e., without supplemental elastic spines) [5].

Figure 1 provides a schematic representation of the MRF-Spine-FLC system that was tested. Elastic spines are attached to the MRF at the middle of the bay. These spines are attached to the MRF by either FLC (which add connection flexibility as well as cap the forces transferred between the MRF and spine), or bolted elastic connections (which

are assumed approximately rigid). One set of tests on the MRF-Spine system used the bolted elastic connections and another set of tests on the MRF-Spine-FLC system used the FLC. The elastic spine has a pinned base, so it adds no additional overturning moment capacity to the combined MRF-Spine or MRF-Spine-FLC systems. As noted previously, the bases of the MRF columns are pinned to enforce a story mechanism in the first story when supplemental elastic spines are not included [5].

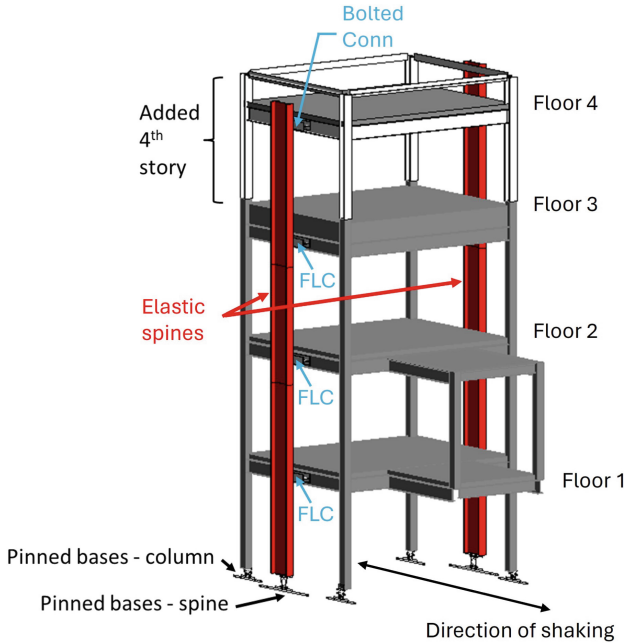


Fig. 1. Schematic representation of the 4-story MRF-Spine-FLC system experimental test specimen.

2.1 MRF-Spine-FLC System for Experimental Testing

The structure and connections for the MRF-Spine-FLC system were designed to meet the goals of experimental testing, namely to mitigate the first-story yield mechanism that occurs when subjected to ground motions scaled to design basis earthquake (DBE) levels, ensure elastic response of the spine for ground motions scaled to maximum-considered earthquake levels (MCE), keep story drifts at or below 2.5% for MCE ground motions, and reduce floor accelerations when changing from approximately “rigid” (i.e., bolted connections) to FLC between the MRF and spine. To accomplish the goals, a W30x148 spine section was selected as NRHA results demonstrated it would remain elastic. The Floor 1 FLC was designed to have an ultimate strength, F_u , of approximately 265 kN (60 kips) to prevent collapse from a story mechanism in story 1. This FLC had an approximate yield force of 185 kN (42 kips), and a design stiffness of 10 kN/mm (56 kip/in) in order

to keep peak story drifts around 2.5%. The Floor 1 FLC design utilized a novel T-shaped yielding element, designed and tested at Lehigh University [3]. The Floor 3 FLC was designed to transfer a force of approximately 45 kN (10 kips) to prevent the formation of a story mechanism in story 3. This Floor 3 FLC utilized two pre-designed UD-40 u-shaped yielding elements from Nippon Steel. The properties of the UD-40 devices can be found in Suzuki et al. “Development of U-shaped steel damper for seismic isolation system” [16]. The Floor 2 FLC is a stabilizing connection with only minimal strength and stiffness which is assumed to be negligible in the NRHA models. The Floor 4 connection is a “rigid” (i.e., bolted elastic) connection with an estimated stiffness of 875 kN/mm (5000 kips/in). This connection was made “rigid” to ease construction challenges during erection of the experimental test specimen.

2.2 Simplified Numerical Modeling

Simple, center-line NRHA numerical models using force-based beam-column fiber elements were created using the Open System for Earthquake Engineering Simulation (OpenSees) to estimate the response of the experimental test specimens [10]. More-in-depth numerical models were subsequently developed to validate design decisions and better estimate the response from experimental testing [2].

Table 1 and Table 2 provide comparisons between the peak story drifts and peak floor accelerations for the MRF, MRF-Spine, and MRF-Spine-FLC systems. Two numerical models of the MRF-Spine system were generated to consider the impacts of increased modal periods between the MRF-Spine system (i.e., with bolted connections) and the MRF-Spine-FLC system. The first model, labeled “MRF-Spine Rigid Conn”, models MRF-Spine connections that are linear elastic and approximately rigid. The second model, labeled “MRF-Spine Flex Conn”, models MRF-Spine connections that are linear elastic but have the same stiffness as the corresponding FLC at each level. Note that the responses of the MRF-Spine Rigid Conn model more closely match the responses from the MRF-Spine experimental tests and therefore are utilized to directly compare benefits, if any, from the addition of FLC.

Figure 2 shows the linear elastic pseudo-acceleration response spectrum for the 1994 Northridge Sepulveda ground motion [1] in comparison with the peak effective pseudo accelerations for the first and second modes, derived from the NRHA results. Figure 2 a) shows the peak effective pseudo accelerations for the MRF, MRF-Spine *Flex Conn* and MRF-Spine-FLC systems, and Fig. 2 b) shows the peak effective pseudo accelerations for the MRF, MRF-Spine *Rigid Conn* and MRF-Spine-FLC systems. As described in [13], the peak effective pseudo accelerations quantify the modal force responses for *nonlinear multidegree-of-freedom (MDF) systems* and are determined from nonlinear restoring force response data collected from NRHA. In this figure, the peak effective pseudo accelerations show the impact that the FLC design has on reducing the accelerations and forces associated with the first and second mode. These peak effective pseudo accelerations are plotted on the x-axis at the modal period associated with each system model.

Figure 2 a) shows the impact of only the force-capping behavior of the FLC on accelerations, as both the MRF-Spine *Flex Conn* and MRF-Spine-FLC systems have

the same modal periods because the connections of both systems have the same stiffness. For this comparison, the force-capping behavior has only a modest effect on the accelerations. Additionally, Fig. 2 a) shows how the addition of the spine decreases the first modal period, and shows how the peak effective pseudo acceleration for the first mode is increased to near-elastic levels from the addition of the spine. There is almost no difference in the first mode peak effective pseudo acceleration response between the MRF-Spine Flex Conn and MRF-Spine-FLC models.

Figure 2 b) shows the total effect of the FLCs, including both the connection flexibility, and the force-capping behavior. In this instance, the acceleration for the second mode is reduced by the period elongation from the localized flexibility of the FLC and from the force-capping behavior of the FLC. The NRHA analysis results in Table 2 show the associated reductions in peak total floor acceleration from the MRF-Spine Rigid Conn system to the MRF-Spine-FLC system, a decrease from 1.383 g to 1.273 g, and a difference of 8%. This decrease of only 8% is smaller than might be anticipated from the reduction in peak effective psuedo accelerations for the second mode. Figure 2 b) also shows the impact of period changes on the pseudo acceleration for the first mode. Similar to the results in Fig. 2 a), the MRF-Spine and MRF-Spine-FLC systems have peak effective psuedo accelerations for the first mode that are larger than for the MRF alone. Also, the longer first mode period of the MRF-Spine-FLC system results in a smaller pseudo acceleration compared to the MRF-Spine Rigid Conn system.

Table 1. Peak Story Drifts (%) for MRF, MRF-Rigid Spine, MRF-Flexible Spine and MRF-Spine-FLC systems for selected experimental T-FLC Design

Story	MRF	MRF-Spine Rigid Conn	MRF-Spine Flex Conn	MRF-Spine- FLC
Story 1	8.98%	2.23%	2.42%	2.54%
Story 2	1.18%	1.86%	1.91%	1.83%
Story 3	1.09%	1.80%	1.97%	1.85%
Story 4	0.74%	1.71%	1.50%	1.39%

Table 2. Peak Total Floor Accelerations (g) for MRF, MRF-Rigid Spine, MRF-Flexible Spine and MRF-Spine-FLC systems for experimental T-FLC Design

Floor	MRF	MRF-Spine Rigid Conn	MRF-Spine Flex Conn	MRF-Spine- FLC
Floor 1	0.883	0.944	1.088	0.972
Floor 2	0.940	1.247	1.314	1.273
Floor 3	0.948	1.000	1.214	1.175
Floor 4	0.882	1.383	1.005	1.0174

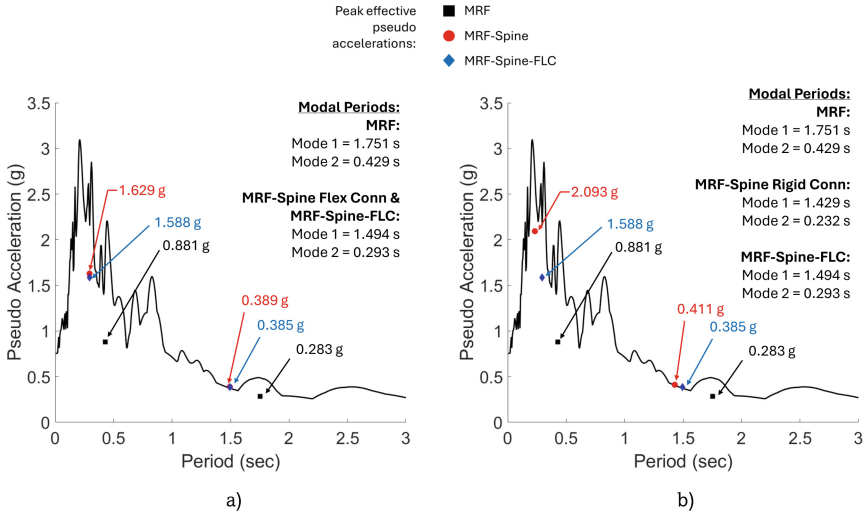


Fig. 2. Northridge acceleration spectrum showing peak effective pseudo accelerations for the a) MRF, MRF-Spine Flex Conn and MRF-Spine-FLC systems and b) MRF, MRF-Spine Rigid Conn and MRF-Spine-FLC systems as designed for experimental testing.

3 Evaluating FLC Designs

While experimental testing provided an opportunity to validate the MRF-Spine-FLC system concept, the testing program did not consider a variety of FLC designs, due to the tight schedule for FLC design and fabrication, and the geometric constraints of the existing 3-story MRF. However, further numerical simulations on the MRF-Spine-FLC system with varying yield strengths, F_y , for the Floor 1 FLC demonstrate the potential advantages of the force-capping behavior inherent to FLC.

The MRF-Spine-FLC study presented here focuses on varying the yield force, F_y , for the Floor 1 FLC in each MRF-Spine-FLC model (MSF); other design properties for the MRF-Spine-FLC system remain unchanged. The stiffness properties of the Floor 1 FLC remain at the design value for the Floor 1 FLC used in the experimental test specimen, 10 kN/mm (56 kip/in), as noted above, and is unchanged for each variation of the MSF model. NRHA was performed for each MSF model, then its response was compared to the responses of the MRF and MRF-Spine Rigid Conn models. Additional comparisons were made against the MRF-Spine Flex Conn model in order to visualize how altering the Floor 1 FLC yield strength impacts the peak effective pseudo accelerations for the first and second modes.

Figure 3 shows that varying the yield force, F_y , of the Floor 1 FLC significantly impacts the accelerations in MRF-Spine-FLC systems. Peak effective pseudo accelerations are plotted in comparison with the Northridge pseudo acceleration spectrum at the corresponding first and second mode periods for the MRF, MRF-Spine Flex Conn, and MSF models. Modal periods of MSF models are the same as the MRF-Spine-FLC model noted in Fig. 2 as there is no variation in Floor 1 FLC stiffness from model to model. Peak effective pseudo accelerations are provided for the first and second modes

for Floor 1 FLC yield force values of 44 kN (10 kips), 89 kN (20 kips), 133 kN (30 kips), 178 kN (40 kips), 222 kN (50 kips), and 267 kN (60 kips). Note that at a yield force of 289 kN (65 kips), the Floor 1 FLC yield force equals the force demand for the Floor 1 MRF-Spine connection of the MRF-Spine, and the Floor 1 FLC does not yield and has no impact on the accelerations.

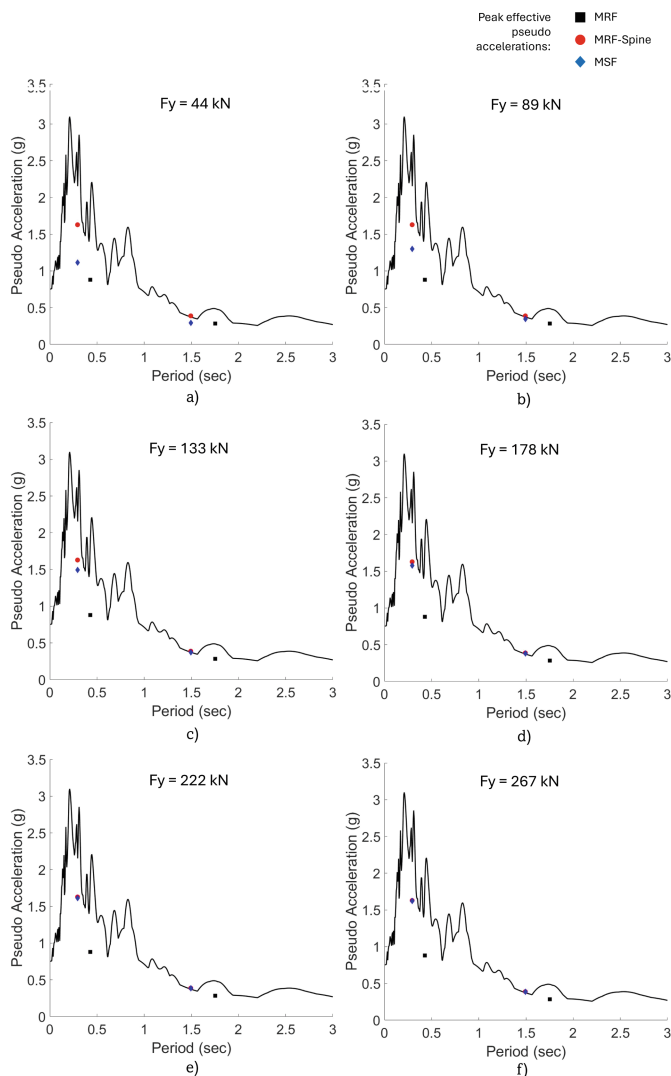


Fig. 3. Northridge acceleration spectrum with peak pseudo accelerations for MRF, MRF-Flexible Spine (MRF-Spine) and MSF where the FLC strength is a) $F_y = 44$ kN (10 kips), $F_y = 89$ kN (20 kips), $F_y = 133$ kN (30 kips), $F_y = 178$ kN (40 kips), $F_y = 222$ kN (50 kips), and $F_y = 267$ kN (60 kips).

Figure 4 provides the difference in Mode 2 peak effective pseudo accelerations between the MRF-Spine Flex Conn model and the MSF models with varying yield strengths. It is clear from Fig. 4 that a lower yield strength in the Floor 1 FLC directly reduces the peak effective pseudo accelerations for Mode 2. Comparing the results shown in Fig. 4 to the peak total floor accelerations given in Table 4 for MRF, MRF-Spine Rigid Conn, and MSF models, it can be seen that the differences in peak effective pseudo accelerations between the MRF-Spine Flex Conn and MSF models provide a good benchmark for beneficial FLC designs. However, a lower yield strength in the Floor 1 FLC also results in a trend of larger story drifts as seen in Table 3. A Floor 1 FLC yield strength must be between 178 kN and 222 kN to maximize the reduction in floor accelerations while meeting the drift target of 2.5% for the experimental test structure. The Floor 1 FLC of the MRF-Spine-FLC system that was tested has an estimated yield strength of 187 kN. This value was estimated from experimental component testing [3].

Table 3. Peak story drifts (%) for MRF, MRF-Spine Rigid Conn, and MSF models of varying yield strength, F_y , for the Floor 1 FLC

Story	MRF	MRF-Spine Rigid Conn	MSF 44kN (10 kips)	MSF 89kN (20 kips)	MSF 133kN (30 kips)	MSF 178kN (40 kips)	MSF 222kN (50 kips)	MSF 267kN (60 kips)
Story 1	8.98%	2.23%	3.85%	3.12%	2.79%	2.57%	2.47%	2.44%
Story 2	1.18%	1.86%	1.31%	1.56%	1.71%	1.82%	1.88%	1.90%
Story 3	1.09%	1.80%	1.12%	1.43%	1.64%	1.82%	1.92%	1.96%
Story 4	0.74%	1.71%	0.88%	1.08%	1.25%	1.37%	1.43%	1.46%

Table 4. Peak total floor accelerations (g) for MRF, MRF-Spine Rigid Conn, and MSF models of varying yield strength, F_y , for the Floor 1 FLC

Story	MRF	MRF-Spine Rigid Conn	MSF 44kN (10 kips)	MSF 89kN (20 kips)	MSF 133kN (30 kips)	MSF 178kN (40 kips)	MSF 222kN (50 kips)	MSF 267kN (60 kips)
Floor 1	0.883	0.944	0.803	0.836	0.852	0.951	1.036	1.069
Floor 2	0.940	1.247	0.985	1.037	1.180	1.264	1.293	1.303
Floor 3	0.948	1.000	0.956	1.035	1.116	1.169	1.190	1.197
Floor 4	0.882	1.383	0.868	0.983	1.022	1.019	1.012	1.006

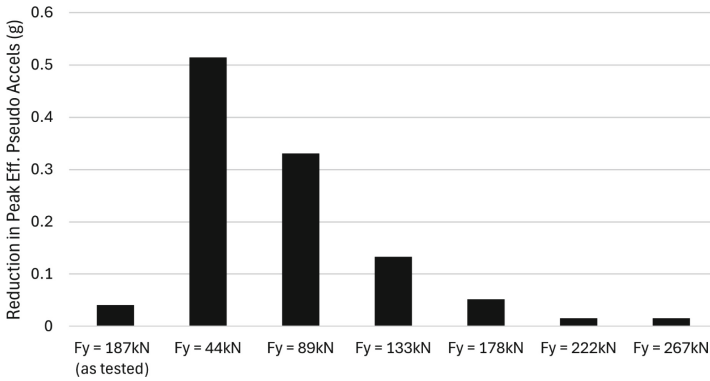


Fig. 4. Reduction in mode 2 peak effective pseudo accelerations between the MRF-Spine Flex Conn model and MSF models for varying Floor 1 FLC yield strengths.

4 In-Depth Numerical Study on Modeling Uncertainty Supported by Experimental Results

The results presented in this study used simplified centerline models of the MRF as a proof of concept for the design. More in-depth numerical modeling and uncertainty quantification were performed to better estimate the expected response of the specimens during experimental testing [2]. The quantification of modeling uncertainty evaluated how different types of modeling choices impacted the estimates of story drift and total floor acceleration responses. The sensitivity study utilized stochastically generated models to assess the variability of the expected response under the presence of uncertainty in modeling the beam composite action, panel zone stiffness and strengths, damping, mass, and yield strength and stiffnesses for both the Floor 1 and Floor 3 FLC.

Results from Astudillo et al. [2] concluded that uncertainty in the yield force and stiffness of the Floor 1 FLC in the Frame-Spine-FLC model had the largest contribution to changes in the total floor acceleration response and was the second largest contributor to changes in drift response, behind uncertainty in MRF panel zone properties. In particular, the study showed that given the uncertainty in the estimates of the Floor 1 FLC yield force, an increased FLC yield force resulted in larger floor accelerations at all floors, and resulted in smaller lower-story drifts and larger upper-story drifts for the Northridge ground motion record. The uncertainty in the properties of the Floor 3 FLC did not have a major effect on the estimates of the global response.

5 Conclusions and Future Work

This study of a 4-story MRF-Spine-FLC system shows that FLC can reduce peak total floor accelerations for MRF-Spine systems. There exists a trade-off between floor acceleration reduction and increasing story drifts when the yield force, F_y , of the FLC is varied. This study indicates some reductions in peak floor accelerations for FLC with yield forces that maintain peak story drifts of the MRF-Spine-FLC system at or below 2.5%.

Expanding the case study to consider MRF-Spine-FLC systems with less strict story drift limits, it is clear that introducing more force capping, through lower FLC yield forces, results in lower accelerations but may increase story drifts. Future work should be done to evaluate the impact of FLC stiffness on the MRF-Spine-FLC system response. In this study, the FLC stiffness remained unvaried as the FLC yield force was varied. It is unlikely that the FLC yield force is easily varied without impacting the stiffness, although future work on designing and testing FLC devices may generate FLC designs that optimize MRF-Spine-

FLC response, without a significant increase in peak story drifts while reducing peak floor accelerations.

Additionally, this study indicates that peak effective pseudo accelerations are a useful tool for understanding the response of different FLC designs for MRFSpine-FLC systems. In this study, reductions in second mode peak effective pseudo accelerations between two models without global flexibility differences are consistent with reductions in total floor accelerations from NRHA between the MRF-Spine and MRF-Spine-FLC systems.

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