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PRELIMINARY NUMERICAL ANALYSIS OF A STRONGBACK COLUMN AS A RETROFIT OF A MOMENT-RESISTING FRAME

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Abstract

Steel moment-resisting frames (MRFs) are widely used in the United States to resist seismic forces. MRFs have many advantages, including high ductility, architectural versatility, and vetted member and connection detailing requirements. However, MRFs require large members to meet story drift criteria. Moreover, strong-column-weak-beam requirements can result in significant member sizes, and – even in the cases where strong-column-weak-beam requirements are satisfied – MRFs can still be vulnerable to story mechanisms in one or a few stories. Recently, the concept of a strongback has been utilized successfully to delay or prevent story mechanism behavior in braced frames. The strongback is represented by a steel truss or column that is designed to remain essentially elastic, thus allowing the system to transfer inelastic demands across stories. Although systems including strongbacks exhibit more uniform story drift demands with building height and reduced peak drift response, the elastic nature of the strongback can also result in amplified higher-mode force demands. This study compares the dynamic response of a baseline MRF to that of a retrofit using a strongback column. Several ground motions are considered to determine which cases produce the largest drift, acceleration, and force demands.

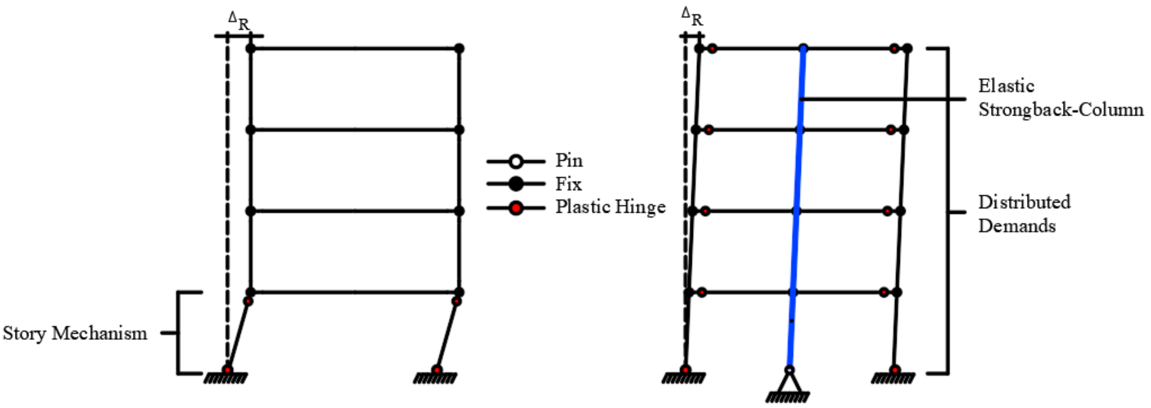
Keywords: strongback, moment-resisting frame, nonlinear dynamic analysis, higher-mode response

1. Introduction

Capacity design is a simplified analysis method used to design for force demands that are intended to remain elastic. In Moment-Resisting Frames (MRFs), this is traditionally accomplished through a strong-column/weak-beam (SC/WB) capacity design approach, where the columns are designed to be stronger than the beams based on equilibrium at the beam-column joint. This promotes the intended yield mechanism in MRFs, which includes flexural yielding at the ends of the beams and column bases. Although SC/WB promotes flexural yielding in the beams over the columns, MRFs are still expected to experience significant inelastic deformation during significant ground shaking, and compliance with SC/WB does not guarantee that yielding will not occur in the columns, even if the frame has been properly detailed [1].

For multi-story MRFs, inelastic response can be non-uniform with building height, producing concentrations of inelastic demands that could lead to story mechanisms; see Fig. 1(a). Re-distribution of these inelastic demands to adjacent stories is traditionally accomplished through column flexural stiffness and strength [1, 2, 3]. Alternatively, a strongback spine, represented by a stiff and strong vertical element or truss that is designed to remain essentially elastic, can provide a defined force path to distribute demands more uniformly with building height; see Fig. 1(b). The strongback is pinned at its base and is not intended to provide supplemental lateral strength [4]. Rather, energy dissipation is provided by the base MRF. The strongback then works jointly with the MRF to transfer inelastic demands across stories. Similar concepts, such as zipper frames [5, 6], tied eccentrically braced frames [7, 8], continuous columns [9 , 10, 11], and elastic dual systems [12] have been studied by other researchers.

Despite being implemented successfully in both research and practice [4, 13], design methods for strongback elements have not been formalized. Traditional capacity design methods are insufficient for systems whose behavior includes substantial nonlinearities, elastic higher-mode behavior, or dependency on the intensity of the ground motion, like that expected for systems employing strongbacks. This study characterizes the dynamic response of a retrofit of a four-story MRF employing a strongback spine-column. Peak story drift, absolute floor accelerations, and story shear forces were compared for a baseline MRF and the MRF retrofitted with a strongback column. The impact of column base fixity and beam composite action on response was also explored. Results from 80 nonlinear dynamic analyses demonstrate that the addition of the strongback column can result in reduced story drift and amplified force and acceleration demands with respect that of the baseline MRF. However, the magnitude of the difference in response between the unretrofitted and retrofitted MRF depends on the inelastic properties of the baseline MRF and the characteristics of the ground motion input.



(a) Moment-Resisting Frame (MRF) (b) MRF with strongback column

Fig. 1 Baseline MRF v. MRF with strongback column

2. Design Overview

Strongback systems are a hybrid of an inelastic seismic-force resisting system an essentially elastic vertical element, or strongback, used to delay or prevent story mechanisms. Since the strongback is designed to remain elastic in every mode, systems employing strongback spines can exhibit near-elastic higher-mode force and acceleration demands [4,15,etc.]. This higher-mode response is fundamentally different from systems which can form yield mechanisms in every mode, thereby limiting the accelerations that can develop in the higher modes. To investigate the difference between a system able to form a story mechanism and systems employing strongbacks, a baseline MRF was compared to the same system employing a strongback retrofit.

2.1. Design of the Moment-Resisting Frame

A baseline MRF consistent with vintage detailing and typical of existing construction for a hospital was used as a control for later comparisons. As an essential facility, the MRF was designed for risk category IV, resulting in an importance factor of 1.5. The baseline MRF was investigated with both pinned and fixed column base conditions. The case with pinned column bases introduced a strong tendency for form a first-story mechanism and was used to emphasize the potential impact of adding a strongback as a retrofit scheme for the worst-case story mechanism scenario.

2.2. Design of the strongback columns as a retrofit

The baseline MRF was retrofitted with a strongback column. Depending on the magnitude of the horizontal irregularity and corresponding demands, a stiff and strong truss or wall [14] could alternatively be used for the strongback spine. The strongback was designed using simplified estimates for the higher-mode force demands [4] to remain elastic under all modes of excitation. Force demands delivered to the strongback column from the formation of a full yield mechanism, like that shown in Fig. 1(b), were also considered. Subsequent nonlinear dynamic analyses confirmed that the strongback column remained elastic under the considered ground motion inputs.

3. Nonlinear Numerical Analysis

To investigate the effects of the near-elastic higher-mode response in systems employing strongbacks, the dynamic response of the baseline MRF and MRF with strongback were compared for multiple ground motion inputs using nonlinear dynamic analysis.

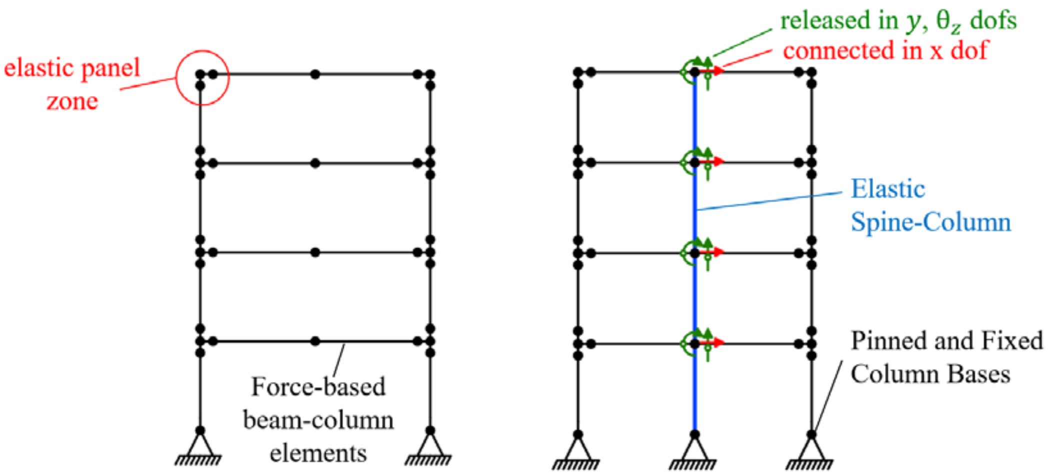


Fig. 2 Numerical models

3.1. Numerical model

Nonlinear dynamic analyses were conducted in OpenSees using two-dimensional models of the four-story MRF and MRF with spine column; see Fig. 2. The impact of fixed versus pinned column bases and composite versus non-composite beams on the response was also investigated. The strongback column was attached to the baseline MRF only in the horizontal direction (x) and released in the vertical (y) and rotational (θ_z) directions. The panel zones were modeled with elastic beam-column elements representative of the geometry of the panel zone region. Beams and columns were modeled using force-based beam-column elements. Rayleigh damping of 2.5% was specified in the first- and fourth mode elastic periods. Other numerical modeling parameters are shown in Table 1.

Table 1. Numerical model properties

Item	Modeling Parameter	Beams	Columns	Strongback column*
Steel Material	Strain hardening, b	0.003	0.003	-
Numerical Parameters	Number of integration points	5	5	-
	Number of fibers along, bf	5	5	-
	Number of fibers along, d	1	1	-
	Number of fibers along, tf	1	1	-
	Number of fibers along, tw	5	5	-
Geometric Transformation	Type	Corotational	P-Delta	Corotational

* Modeled with an elastic beam-column element.

3.2. Modal periods

The modal periods from an eigenvalue analysis of the numerical models are shown in Table 2 for the cases with pinned and fixed column bases and composite and non-composite beams. Inclusion of the fixed column bases and composite beam resulted in increased stiffness and reduced periods. Likewise, the addition of the strongback column, a very stiff element, resulted in reduced periods with respect to the baseline MRF.

Table 2. Modal periods

Periods. T_n [s]	Baseline MRF				MRF with strongback column			
	Pinned column base		Fixed column base		Pinned column base		Fixed column base	
	Non-composite	Composite	Non-Composite	Composite	Non-composite	Composite	Non-Composite	Composite
Mode 1	1.55	1.37	1.17	1.01	1.13	0.97	1.34	1.16
Mode 2	0.40	0.35	0.31	0.27	0.22	0.20	0.22	0.21
Mode 3	0.23	0.21	0.21	0.19	0.09	0.09	0.09	0.09
Mode 4	0.14	0.14	0.14	0.13	0.09	0.09	0.09	0.09

3.3. Ground motions

Numerical models of the baseline MRF and MRF with strongback column were subjected to forty site-specific ground motions for Oakland, CA. These ground motions were selected based on a uniform hazard spectrum with a 10% probability of exceedance in 50 years [16]. Peak response parameters were studied for the suite of 40 two-component (fault normal and fault parallel) ground acceleration records; see Fig. 3(a). The Design and Maximum Considered Earthquake response spectra (DE and MCE) for the Oakland site are shown in Fig. 3.

3.4. Representative ground motion

A representative ground motion with a near-one scale factor was selected from the ground motion suite to study the response for a single ground-motion record. The pseudo-acceleration response spectrum for this ground motion is shown in Fig. 3(b) (station name: Sepulveda VA Hospital, event name: 1994 Northridge). Pseudo-accelerations corresponding to the modal periods are tabulated in Table 3. Note, the second-mode periods are in the acceleration-sensitive range of the response spectrum. These higher modes were expected to exhibit a near elastic response due to the presence of the strongback column.

Table 3. Spectral pseudo-accelerations for Northridge, Sepulveda Valley Hospital record.

Spectral pseudo-accel. S_A [g]	Baseline MRF				MRF with strongback column			
	Pinned column base		Fixed column base		Pinned column base		Fixed column base	
	Non-composite	Composite	Non-Composite	Composite	Non-composite	Composite	Non-Composite	Composite
Mode 1	1.04	1.13	1.01	1.27	1.12	1.43	1.11	1.06
Mode 2	2.44	1.78	1.43	1.52	1.22	1.16	1.21	1.08
Mode 3	1.25	1.08	1.08	1.15	0.96	0.96	0.96	0.96
Mode 4	1.01	1.01	1.01	1.05	0.96	0.96	0.96	0.96

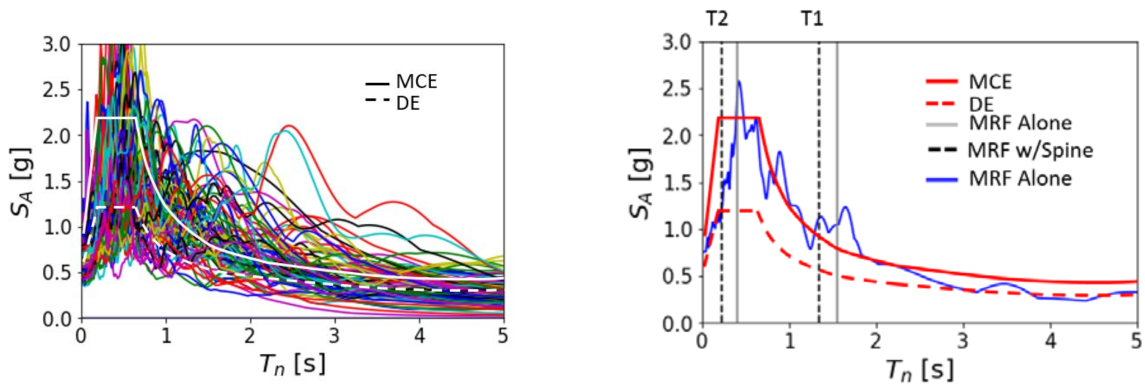


Fig. 3 – Pseudo-acceleration response spectra for: (a) Oakland ground motion set and (b) Northridge, Sepulveda Valley Hospital record.

4. Results for representative ground motion

Initially, the response for each model was compared using the representative Northridge ground motion. Peak story drift ratios, absolute floor accelerations, strongback column moments, and story shears were compared for both the MRF and MRF with strongback. In the following plots, results for the pinned and fixed column bases are shown on the left and right subplots, respectively, for the baseline MRF (black lines) and MRF with strongback column (blue lines). The plots also show the difference in behavior for non-composite (solid line) versus composite (dotted line) beams.

4.1. Peak story drift ratio

Fig. 4 shows the peak story drift ratio, θ_j, for when the column bases were pinned [Fig. 4(a)] and fixed [Fig. 4(b)]. Peak story drift ratio was defined by:

$$\theta_j = \max_t \left| \frac{u(t)_{j+1} - u(t)_j}{h_j} \right| \quad (1)$$

u_j = the displacement at floor j; u_{j+1} = the displacement at floor $j+1$; h_j = jth story height.

The baseline MRF with pinned column bases exhibited concentrations of story drift in the first story, indicative of a first-story mechanism. In contrast, the addition of the strongback column resulted near-uniform story drift ratios across all stories, reducing the peak story drift demand from approximately 6.5% to 2.5% for the pinned base case. As the MRF with fixed-column bases had less of a tendency to form a story mechanism, the impact of the strongback column on peak story drift demand for the MRF with fixed column bases was less dramatic. Story drifts decreased with the inclusion of composite beams, but trends remained similar to the non-composite beam case.

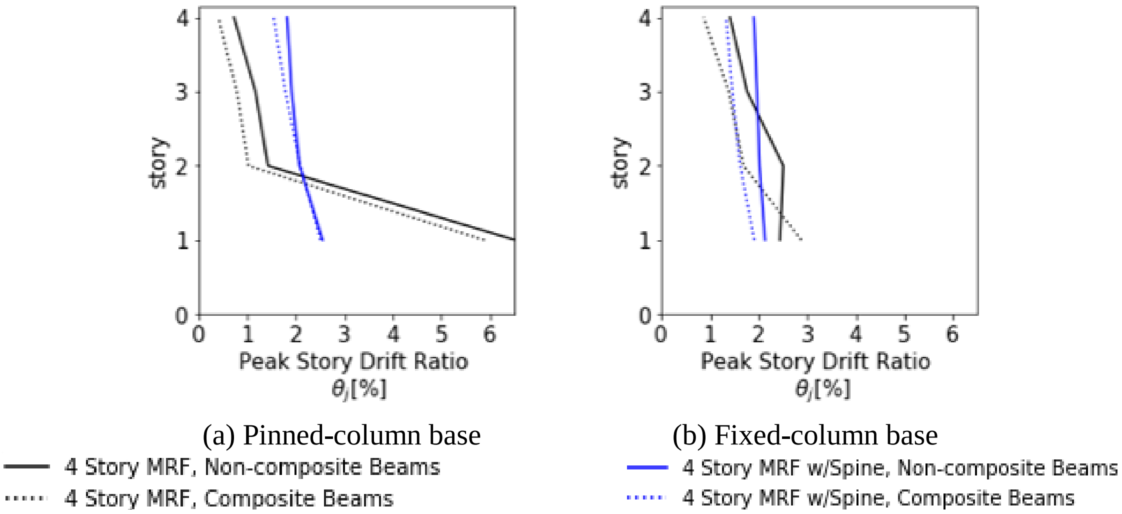


Fig. 4 – Peak story drift ratio

4.2. Peak story shear

Fig. 5 shows the peak story shear forces, V_j, for when the column bases were pinned [Fig. 5(a)] and fixed [Fig. 5(b)]. Story shears were obtained by summing the horizontal resisting forces of the columns of each story. The peak story shear increased regardless of column fixity when the strongback column was included in the analysis. This is partly due to the reduced period and added stiffness of the strongback column. With composite beams, story shears also tended to increase, though this trend was imperfect. Force reversals associated with the higher modes resulted in a different height-wise distribution of story shear demands in the MRF and MRF with strongback column, particularly for the base shear and upper story shears. The increase in story shear demands was most apparent for the pinned-base MRF, where the story shear forces in the baseline MRF were limited by the formation of a story mechanism. In contrast, the strongback column was designed to remain elastic, and shear forces could continue to accumulate with increasing ground motion intensity for the pinned-base MRF with strongback. The increase in story shear demands was less apparent for the fixed-base MRF as it had less of a tendency to form a story mechanism.

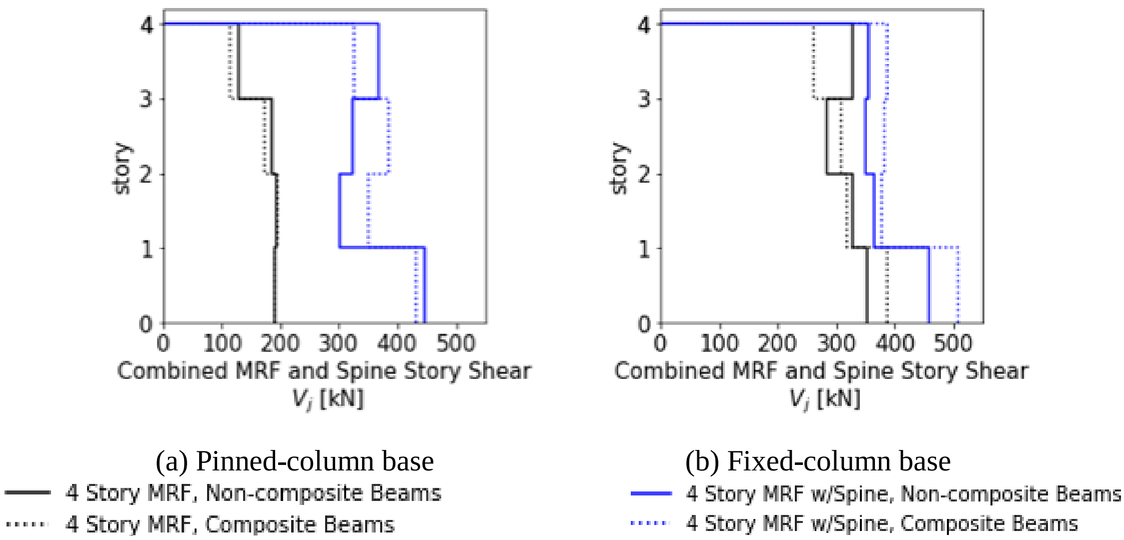


Fig. 5 – Peak story shear

4.3. Peak absolute floor accelerations

Fig. 6 shows the peak absolute floor acceleration, a_j, for when the column bases were pinned [Fig. 6(a)] and fixed [Fig. 6(b)]. For the pinned-base MRF, the peak absolute accelerations were amplified at every floor due to the presence of the strongback column and near-elastic higher-mode contributions. These accelerations were limited in the pin-base MRF because of its tendency to form a story mechanism. In contrast, except at the roof level, accelerations were higher in the fixed-base MRF. This is because both the MRF and MRF with strongback for the fixed column bases did not form a story mechanism.

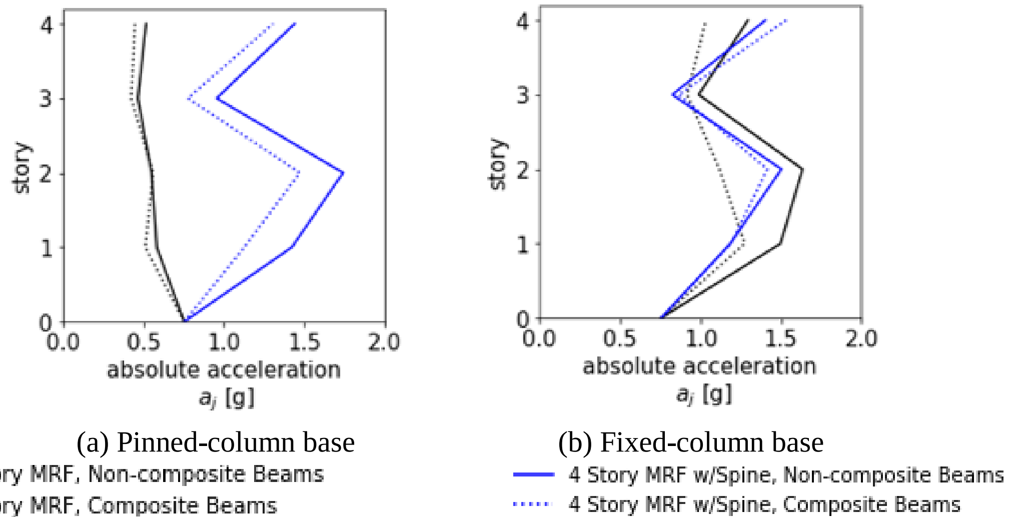


Fig. 6 – Peak absolute floor accelerations

4.4. Strongback column bending moments

Fig. 7 shows the peak bending moments in the strongback column, M_s, for when the column bases were pinned [Fig. 7(a)] and fixed [Fig. 7(b)]. Fig 7 also shows 70% of the strongback column yield moment (magenta line) as a proxy for the strength of the spine column. The limit state of inelastic lateral-torsional buckling is expected to control but is not shown in these plots for simplicity. The strongback column selected for this study remained elastic for the ground motion considered. The moment demands on the strongback column for the composite and non-composite beams and fixed and pinned column bases were similar. Although the moment diagrams shown in Fig. 7 represent peak values where the moments do not occur in the same time instant, moment response histories for the strongback column resembled the moment diagram of a simple supported beam.

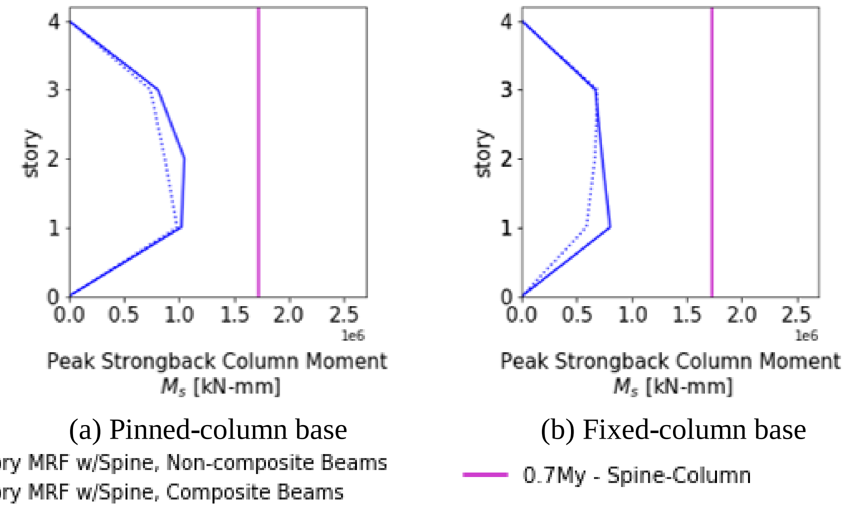


Fig. 7 – Peak moments in spine

5. Results for multiple ground motions

To investigate differences in behavior for different ground motion inputs, 80 nonlinear dynamic analyses were conducted using the site-specific ground motion records for Oakland, CA selected for a uniform hazard of 10% in 50 years. The ground motions were sorted based on decreasing peak story drift ratio for the MRF with strongback column and pinned column bases; i.e., records resulting in the largest and smallest maximum peak story drift ratio are near the left and right boundary of the plot, respectively. The plots also show the difference in behavior for non-composite (solid line) versus composite (dotted line) beams.

5.1. Maximum peak response over all stories

The maximum peak story drift ratio, absolute floor acceleration, and story shear demands over all four stories were plotted for each ground motion record for the 80 analyses and for both column base conditions; see Fig. 8 and 9. The baseline MRF and MRF with strongback response parameters are represented by the blue and red lines, respectively.

5.1.1. Pinned column bases

Fig. 8(a) shows a comparison between the maximum peak absolute accelerations, story drift ratios, and story shears when the column base was pinned. For almost every ground motion, the baseline MRF with pinned column bases formed a story mechanism. For all records, the strongback column significantly reduced the story drift demand, even for those cases when the baseline MRF exhibited collapse. The magnitude of the amplification in accelerations and story shear forces relative to the baseline MRF was very dependent on the ground motion considered. In some cases, the addition of the strongback column resulted in amplified acceleration response while other cases resulted in similar acceleration response. For all ground motions, the MRF with strongback column exhibited larger story shear demands.

5.1.2. Fixed column bases

Fig. 8(b) shows a comparison between the maximum peak absolute accelerations, story drift ratios, and story shears when the column base was fixed. In contrast to the pinned column base cases, the addition of the strongback did not result a significant difference in acceleration or drift response because the MRF with fixed column bases did not exhibit a significant tendency to form a story mechanism. Like the pinned case, story shears increased in the MRF with strongback column relative to the baseline MRF because of the additional strength provided by the strongback column.

5.2. Ratio of MRF to MRF with strongback response

To compare the difference in response of the baseline MRF to the MRF with strongback on a story-by-story basis, the ratio of the baseline MRF ($\cdot_{MRF}$)-to-MRF with strongback ($\cdot_{spine}$) response was defined at each story. The maximum of this ratio for story shear, $V_{j,spine}/V_{j,MRF}$, absolute acceleration, $a_{j,spine}/a_{j,MRF}$, and story drift ratio, $\theta_{j,MRF}/\theta_{j,spine}$, is plotted in Fig. 9 for each ground motion.

5.2.1. Pinned column bases

Fig. 9(a) shows the maximum ratios when the column bases were pinned. The presence of the strongback column resulted in significant reductions in story drifts for most ground motions (between 1 to 6 times the story drift response for the MRF without the strongback column). Depending on the ground motion, the accelerations and story shears were amplified with respect to the baseline MRF by 1.5 to 4.5 times and 2 to 3 times, respectively.

5.2.2. Fixed column bases

Fig. 9(b) shows the maximum ratios when the column bases were fixed. Although story drifts were reduced with the strongback column, the reduction was less significant for the fixed column bases than for the pinned column bases. The maximum ratio of the story drift ratio, accelerations, and story shear response was between 1 to 2 for most of the ground motions, indicating similar behavior for the MRF and the MRF with strongback when the column bases were fixed.

6. Summary and Conclusions

A strongback column was introduced as a retrofit of a moment-resisting frame (MRF) to mitigate story mechanism behavior. Results were compared to those of a baseline MRF in terms of story drift ratio, absolute floor accelerations, and story shear forces for models with fixed and pinned column bases and composite and non-composite beams. The baseline MRF with fixed column bases had little tendency to form a story mechanism. As such, the inclusion of the strongback column did not significantly reduce story drift demands or increase acceleration and story shear force demands. In contrast, the MRF with pinned column bases exhibited significant story drift demands in the first story, consistent with a first-story mechanism. Introducing the strongback column resulted in more uniform drift demands over the building height and significantly reduced the first-story peak story drift ratio (60% reduction). As a trade-off, story shears and accelerations approximately doubled with the inclusion of the strongback column. The magnitude of this increase was highly dependent on the properties of the ground motion excitation. The results of this study indicate that the benefits including the strongback spine as a retrofit depends on the tendency of the original system to form a story mechanism and the ground motion characteristics in the first and higher-mode periods.

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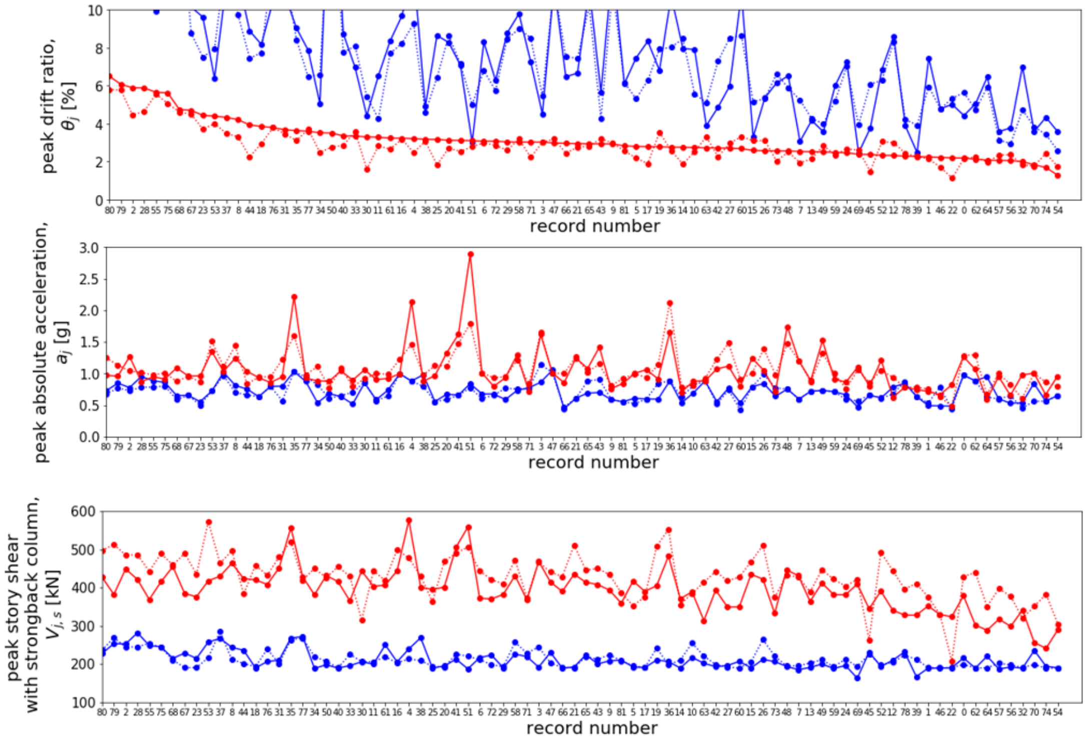
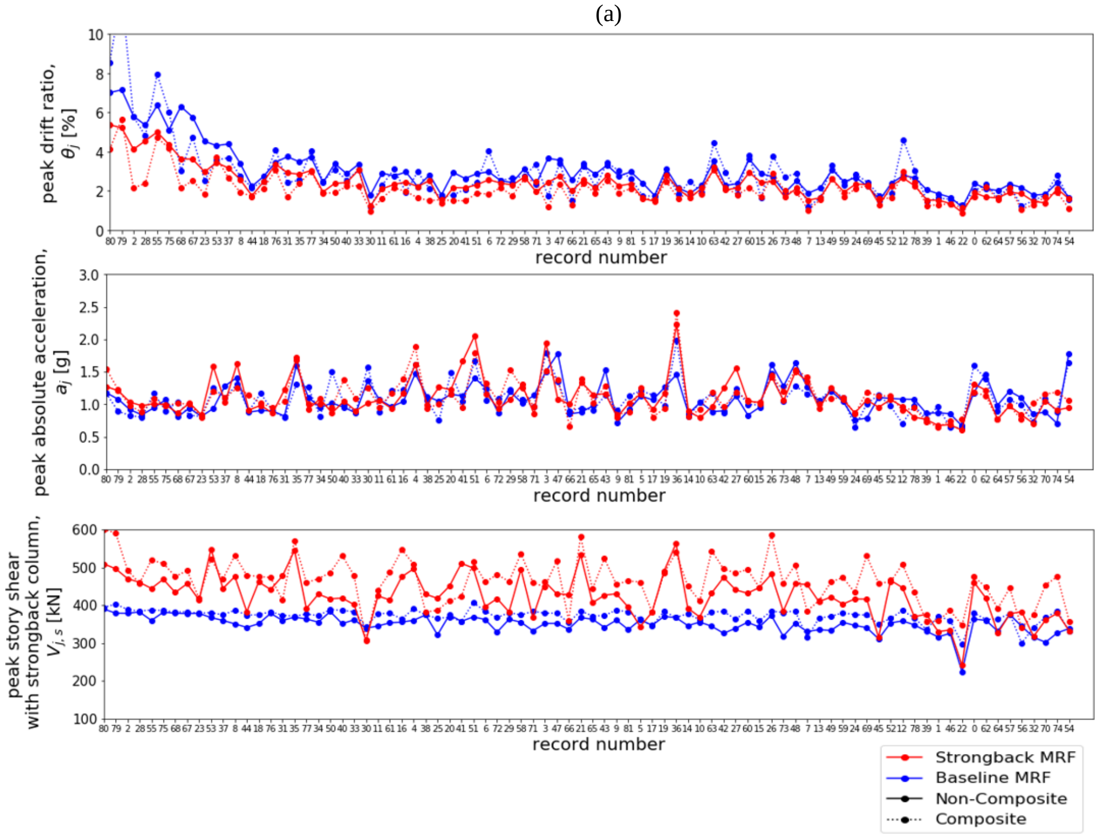
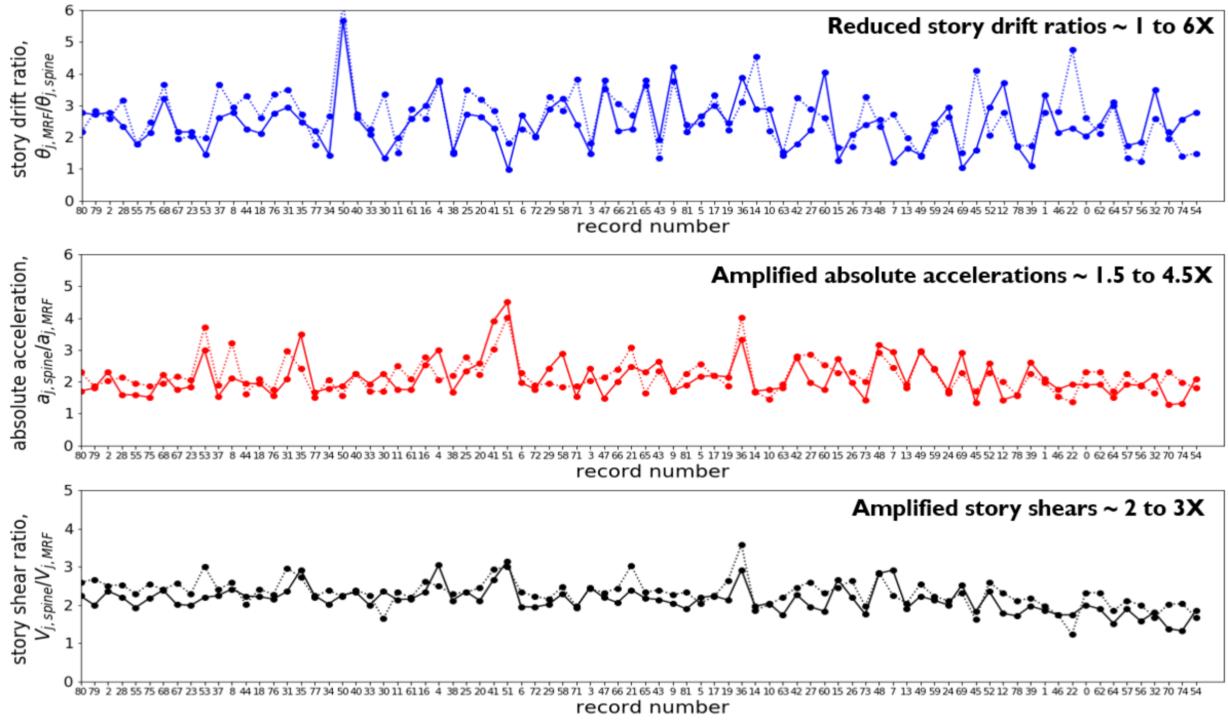


(a)

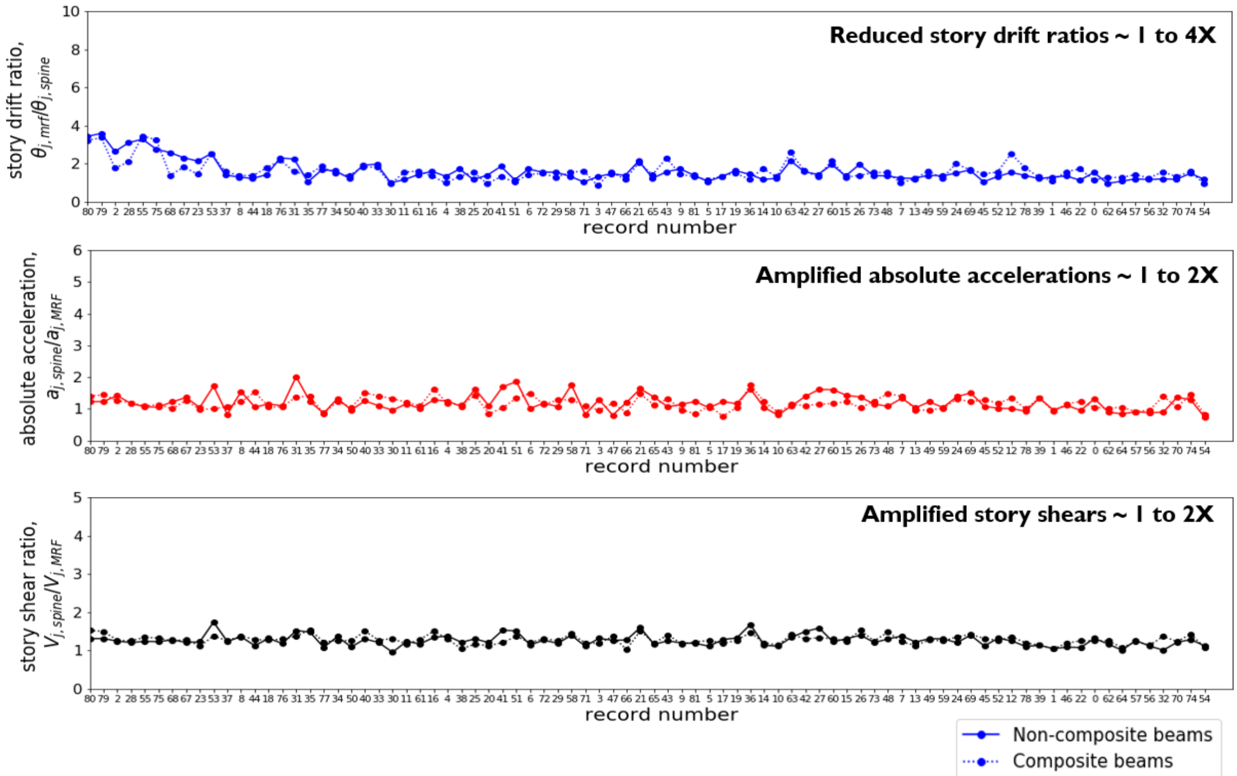


(b)

Fig. 8 – maximum of peak story drift ratio, absolute acceleration and story shear over all stories for: (a) pinned column bases and (b) fixed column bases.



(a)



(b)

Fig. 9 – maximum of peak story drift ratio, absolute acceleration and story shear over all stories for: (a) pinned column bases and (b) fixed column bases.

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