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CONCEPTS TO MINIMIZE EARTHQUAKE-INDUCED COLUMN AXIAL SHORTENING IN STEEL MOMENT-RESISTING FRAMES

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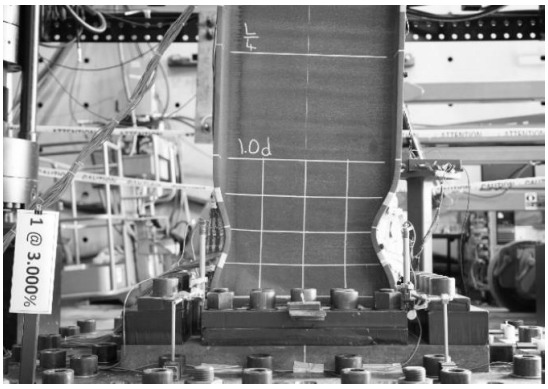
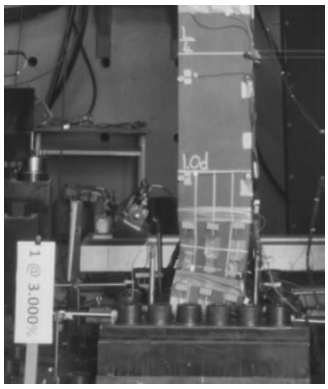
Abstract. *Capacity-designed steel moment-resisting frames (MRFs) dissipate the seismic action through inelastic flexural yielding of protected zones located at the beam ends and the first story column bottom end. During low-probability of occurrence seismic events, flexural yielding is typically followed by local and/or member buckling that could potentially lead to steel MRF global collapse. Experiments of steel columns under cyclic loading underscore the influence of residual axial shortening on the overall column stability. Particularly, residual column axial shortening may cause slab tilting. In turn, the ability for post-earthquake structural repairs in columns may also be significantly compromised. This paper explores an alternative concept aiming to protect the steel MRF column integrity and at the same time minimize axial shortening during an earthquake event. Unlike the traditional seismic design practice, column base connections are designed to dissipate the seismic demands by tuning a stable inelastic dissipation mechanism. The concept is explored by means of nonlinear response history analyses of a case-study steel MRF frame building. Limitations and suggestions for future work are also discussed.*

1 INTRODUCTION

Steel moment-resisting frames (MRFs), are often designed with ideally fixed column base connections. In this case, steel columns within the local compactness limits of current seismic provisions [1], [2] are expected to exhibit inelastic flexural demands during an earthquake. This is often followed by cyclic buckling even at modest lateral drift demands. In turn, column axial shortening occurs [3]–[5]. Shown in figure 1 is an example of a damaged W24x84 column subjected to a symmetric cyclic lateral loading combined with a compressive axial load of 20% of yield axial load during the first cycle of the 3% drift amplitude [3]. At this lateral drift demand, the observed axial shortening was about 30mm and the reserve flexural resistance of the steel column was 70% of the peak moment demand.



(a)



(b)

Figure 1. Residual column axial shortening of a full-scale W24x84 steel column at 3% lateral drift demand (tests conducted by [3]): (a) web view and (b) flange view

Fixed column bases are idealized in two principal ways. The first one includes exposed column base (XCB) connections, common in low-rise buildings and the second one features embedded column base (ECB) connections, which are more common in mid-to-high-rise buildings. Grauvilardell et al. [6] provide a comprehensive review of research conducted on both types of column base connections. In a typical XCB configuration, a steel column is welded through a complete joint penetration to a base plate, which is tied to the reinforced concrete (RC) foundation with anchor rods. A grout layer is often placed between the base plate and the RC footing. Fixity of an XCB connection under axial, shear, flexural load demands is provided through a number of resisting mechanisms including base plate bearing against the grout layer, or the RC foundation, flexural resistance of the base plate, axial and shear resistance of anchor rods, and friction between the base plate and the grout layer or the RC foundation. A shear key is common to provide resistance against shear demand [7]. In typical ECB configurations, a steel column is welded to a base plate, which is embedded into the RC foundation. Wide-flange column cross-sections comprise stiffeners, which are usually welded on both sides of the column flanges at the RC foundation surface level. The axial and shear force demands are resisted through bearing of the column flanges as well as the base plate against the RC foundation [8]. When the bearing capacity of the RC foundation is sufficient, the flexural resistance of the steel column is larger near the RC

foundation surface level, which leads to steel column inelastic behavior above the RC footing during an earthquake. Experiments on ECB connections [8]–[10] suggest that the elastic concrete bearing deformation provides a flexibility to the ECB connection.

In recent studies, column base connections exhibiting energy dissipation characteristics [11]–[18] have been investigated. These studies suggest that, compared to the ideally fixed case, a column's inelastic deformation capacity may be enhanced if column base connections participate in the energy dissipation. Aspects of column base repairability have also been examined.

This paper explores the concept of dissipative column base connections within steel MRF systems designed in seismic regions. The endeavor focuses on how to control column axial shortening in *lieu* of recent experimental findings associated with the ductility of wide flange steel columns under cyclic loading [3], [4]. The concept of dissipative column base connections is explored by means of system-level nonlinear response history analyses to evaluate their efficiency in controlling column axial shortening.

2 DISSIPATIVE COLUMN BASE CONNECTION CONCEPTS

Experimental studies on XCB connections suggest that XCB connections with controlled anchor-yielding exhibit large plastic deformation capacity [7], [15]. If the base plate exhibits flexural yielding [7], it is common to observe undesired weld cracks between the column and the base plate. Others [19] have found that when leveling nuts are employed, the ductility of the anchor rods is reduced. This is because the base plate is in contact with the leveling nuts once the anchor rods experience tensile inelastic straining. Structural design details to alleviate these problems comprise anchor rods designed to be the only yielding component of the XCB. Leveling nuts are also prohibited [20]. Anchor rods can be replaced. Moreover, gaps due to rod deformations can be filled [15], [17]; therefore, the anticipated anchor rod residual deformations may not be critical in the aftermath of earthquakes. This paper explores more the concept of controlled anchor rod yielding in XCB connections.

In ECB connection configurations, a dissipative column base may be realized by activating the foundation itself. Physical testing on ECB connections suggests that the ones that fail by crushing due to concrete bearing exhibit a pinching hysteretic behavior without experiencing strength degradation prior to 6% lateral drift demands [8]. Figures 2a and b illustrate the effect of RC foundation cracking on the hysteretic behavior of ECB connections. Figure 2c and d shows the same effect on column axial shortening while the lateral drift demands increase. In both cases the results are compared with ideally fixed ECBs with elastic RC foundations (dashed lines). The results are obtained through continuum finite element (CFE) simulations of a 3.9 m long W24x146 column subjected to a symmetric cyclic lateral loading history coupled with a compressive axial load of 20% of the axial yield strength (test conducted by [3]). Rotational springs (i.e., rigid in translational directions) coupled to the CFE model approximate the hysteretic flexural behavior of concrete-bearing-critical ECB connections.

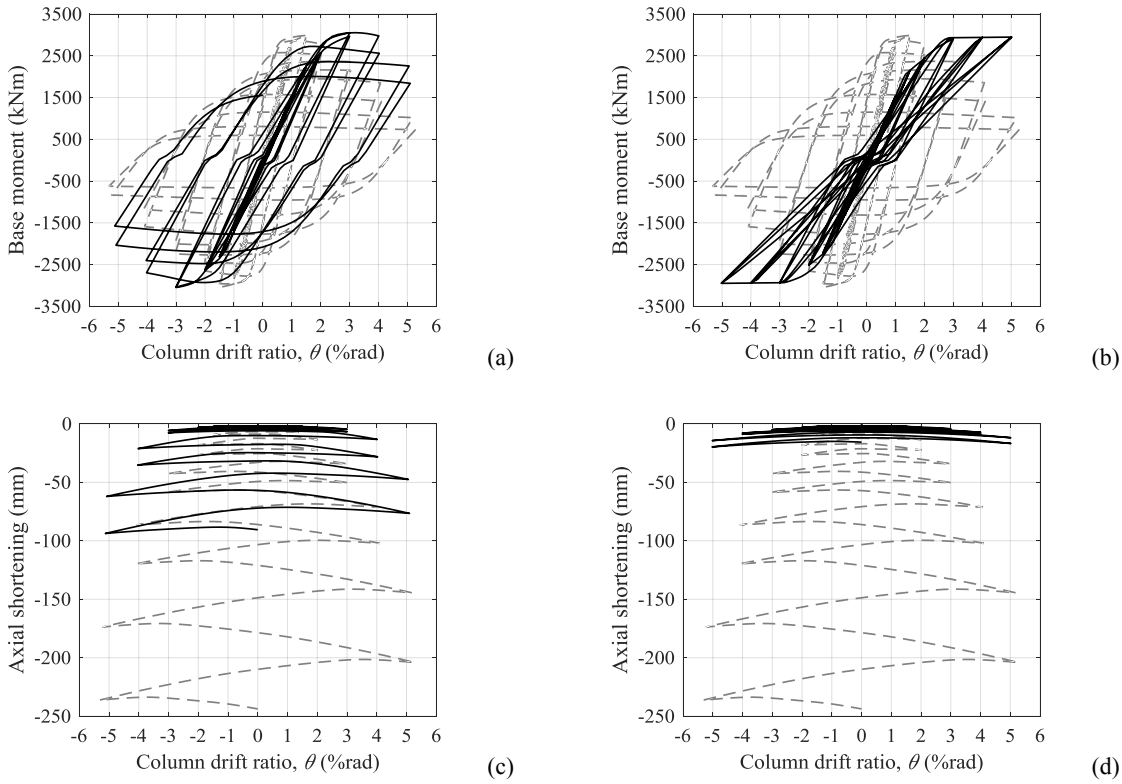


Figure 2. Effect of dissipative column base connections on (a and b) base moment - column drift ratio relation and (c and d) residual column axial shortening - (dashed lines indicate the fixed-base connection [21])

These point hinge models have (i) an ultimate flexural resistance larger than that of the steel column (balanced ECB) (figures 2a and c) and (ii) an ultimate flexural resistance smaller than that of the steel column (figures 2b and d). This is the definition

of the dissipative ECB connection. More details of the CFE modeling approach are discussed in [21]. In figure 2, the column drift ratio is computed based on the column top lateral displacement over the column actual height (= original height minus column axial shortening, if any). Axial shortening is defined as the vertical displacement of the middle node of the column top surface. In balanced ECB connections till the base moment reaches its maximum flexural resistance, the ECB also yields. Referring to figure 2a, the contribution of the ECB connection to the total rotation delays the onset of column cross-sectional local buckling. Hence, the column axial shortening is reduced for a given loading history compared to the ideally fixed column (figure 2c). Referring to figure 2b, the hysteretic behavior of the column base connection is governed by pinching. Hence, the concrete bearing failure governs the total deformation of the column-ECB assembly. However, the resultant column axial shortening is negligible in this case (figure 2d). On the other hand, in concrete-bearing-critical dissipative ECB, the amount of energy dissipation is small because of the pinching behavior. Moreover, extensive concrete damage due to cracking may not be preferred from a repairability standpoint since the repair of the crushed concrete may be impractical. An alternative concept that is currently explored for wide-flange steel columns could be to promote yielding of the embedded steel column part inside the foundation without any profound foundation damage due to cracking. In this case, the steel column should be de-bonded from the RC foundation. Potential instabilities of the embedded steel column web are prohibited since the web is restrained by the surrounding concrete, which should remain elastic, thus enabling controlled rocking of the embedded part of the steel column. This paper explores conceptually this concept by means of nonlinear response history analyses of steel MRF systems.

3 DISSIPATIVE COLUMN BASE MODELS FOR FRAME SIMULATION

In order to explore the seismic performance of steel MRFs with dissipative column base connections, two types of mechanics-based models are developed. The first one, which is applicable for XCB connections, is described in detail in [20]. Figure 3a shows the overview of the developed XCB model. The model comprises elements, which individually simulate the behavior of each component of an XCB connection. Therefore, depending on the damageable component, the hysteretic behavior of the XCB can be properly characterized without supplemental component test calibrations. In figures 3b and 3c, two representative model validations are presented. Specimen #2 tested by Gomez et al. [7] and specimen Fix-Ab-N=0.1NyC tested by Takamatsu and Tamai [17] are adopted for this purpose. The former XCB specimen (#2) comprises a 355.6 x 355.6 mm base plate with 25.4 mm thickness anchored with 4 rods (19.1mm nominal diameter) at each corner of the base plate. The base plate is resting on a grout layer. The W8x48 cantilever column remained elastic throughout the imposed lateral loading history. Leveling nuts are used for the erection process. The second specimen (Fix-Ab-N=0.1NyC) comprises a 400 x 400 x 50 mm base plate with 200 x 200 x 12mm hollow section column resting on a stiff steel beam foundation tied with 4 rods (35mm nominal diameter) at each base plate corner. Compressive constant axial load of 10% of the column yield axial force is applied in addition to the lateral cyclic loading demand. Leveling nuts were not used in this case. Moreover, the steel column and base plate were designed to remain elastic. As shown in figures 3b and c, in both cases, the proposed model captures the base moment - column drift relation with a relatively good accuracy. The agreement between measured and simulated data is noteworthy when the leveling nuts are used (see figure 3b) or when the base plate exhibits yielding. Same observations hold true in the presence of axial compressive load (see figure 3c). However, the strength loss due to anchor rod fracture, which was observed in specimen #2 during the first excursion of 7% drift is not considered in the model. However, this occurs at lateral drift demands that P-Delta effects control the earthquake-induced collapse of steel MRFs [22], [23].

The second model that is developed, represents a dissipative ECB connection that allows for controlled rocking/sliding inside the RC footing. The model is developed in the open-source structural analysis platform OpenSees [24]. It comprises a point hinge model that represents the moment-rotation relation of a dissipative ECB connection. Figure 4 shows the simulated result of an elastic cantilever IPE400 (equivalent to W16x45) column to the RC footing system. From this figure, the anticipated hysteretic behavior of the steel column-RC footing assembly is stable even at relatively large lateral drift demands (6% rads).

4 NONLINEAR RESPONSE HISTORY ANALYSIS OF 4-STORY MRF WITH DISSIPATIVE EMBEDDED COLUMN BASES

This section investigates the potential of dissipative ECBs in mitigating the residual column axial shortening in steel MRFs. This is explored by means of nonlinear frame simulations. While both types of column base connections are of interest to the authors, herein emphasis is placed on the embedded type. The reader is referred to [20], [25] for a more in depth discussion on the dissipative XCB type connection.

A case study steel MRF is used to explore the influence of dissipative ECB connections on the steel MRF's seismic performance. The results are compared with the ideally fixed MRF system. The benchmark case-study steel MRF has been designed as discussed in a prior study by the second author [22]. In brief, the building is located in urban California (seismic design category D and site class D). A plan an elevation view of the building are shown in figure 5. The steel building design satisfies the requirements of the current American provisions [2], [26]–[28]. Steel beams and columns are designed with ASTM A992 Gr. 50 steel (nominal yield stress, f_y = 345MPa). The member sizes are shown in figure 5b. Because the steel MRF with dissipative ECBs does not directly satisfy the drift requirements according to ASCE 7-16 [26] due to the inherent ECB flexibility, the member sizes are slightly adjusted compared to the fixed-based MRF with a marginal increase on the total steel weight compared to the fixed-base case. The first mode periods of the steel MRF designs coincide (The first mode natural period T_1 = 1.32s and 1.33s for the fixed base and dissipative ECB steel MRFs, respectively).

A 2-dimensional (2D) numerical frame model of the steel MRFs is developed in OpenSees. A concentrated plasticity approach is adopted to model the nonlinear behavior of the structural members. The point hinge models feature the modified Ibarra-Medina-Krawinkler (IMK) deterioration model [29]–[32]. The additional lateral resistance coming from the gravity framing is also considered in the 2D model as discussed in [22]. Rayleigh damping with 2% damping ratio assigned at 1st and 2nd modes of each frame is incorporated in the way discussed in [33]. Second-order effects are explicitly considered.

Nonlinear response history analysis (NRHA) is conducted. Since the present study is exploratory, one ground motion record obtained from the Tohoku earthquake in Japan in 2011 is employed. The ground motion is provided by the Japan Meteorological Agency. The ground motion record is the North-South component measured at Wakuyacho Shinmachi in Miyagi prefecture [34]. The measured acceleration history is filtered as explained in [20]. Figure 6 shows the 5% damped elastic absolute acceleration and relative displacement response spectra of the scaled ground motion. This is compared with the design basis spectrum (DBE) as well as the spectrum corresponding to a maximum considered earthquake (MCE) seismic intensity [26]. The adopted seismic signal is a long duration record according to the 5-95% significant duration metric [35], [36].

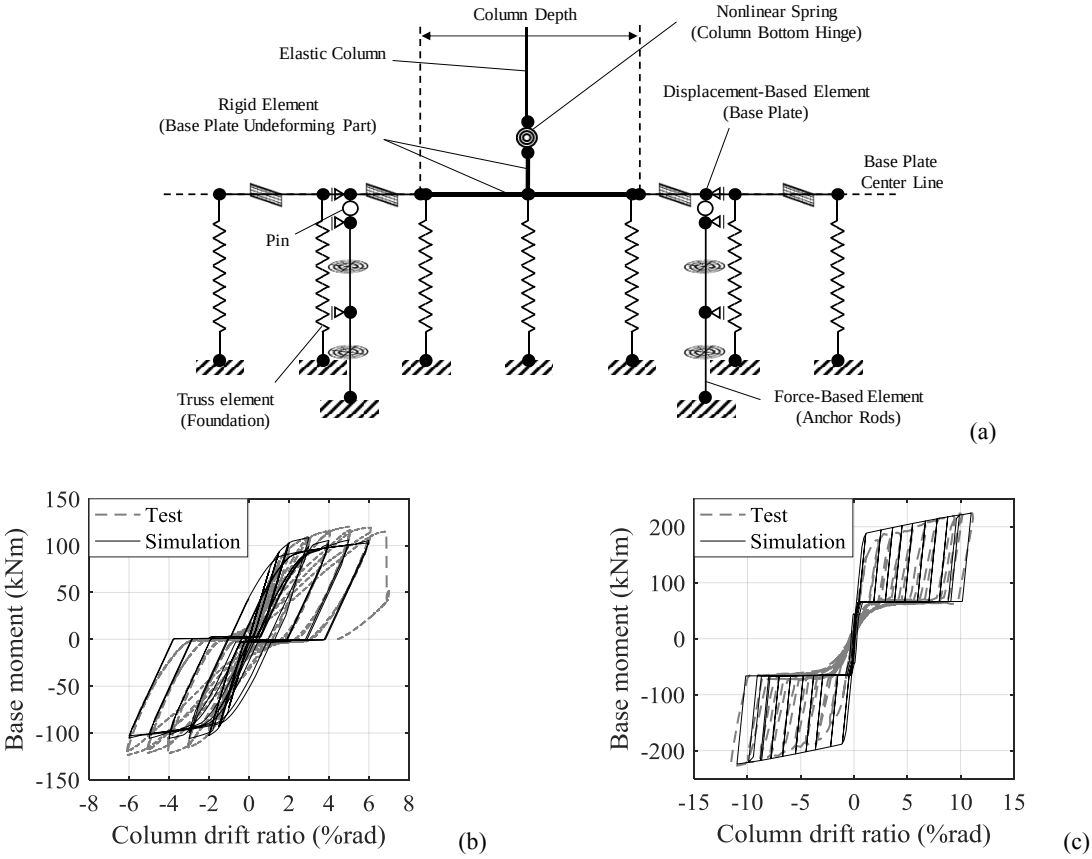


Figure 3. (a) XCB model for 2-D Frame Simulation (adopted by [20]) and comparisons between simulation result and test results obtained from (b) specimen '#2' from [7] and (c) specimen 'Fix-Ab-N=0.1NyC' from [17]

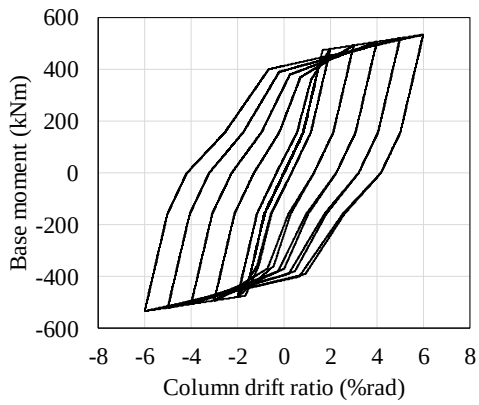


Figure 4. Representative dissipative ECB model response for IPE400 column (Equivalent to W16x45)

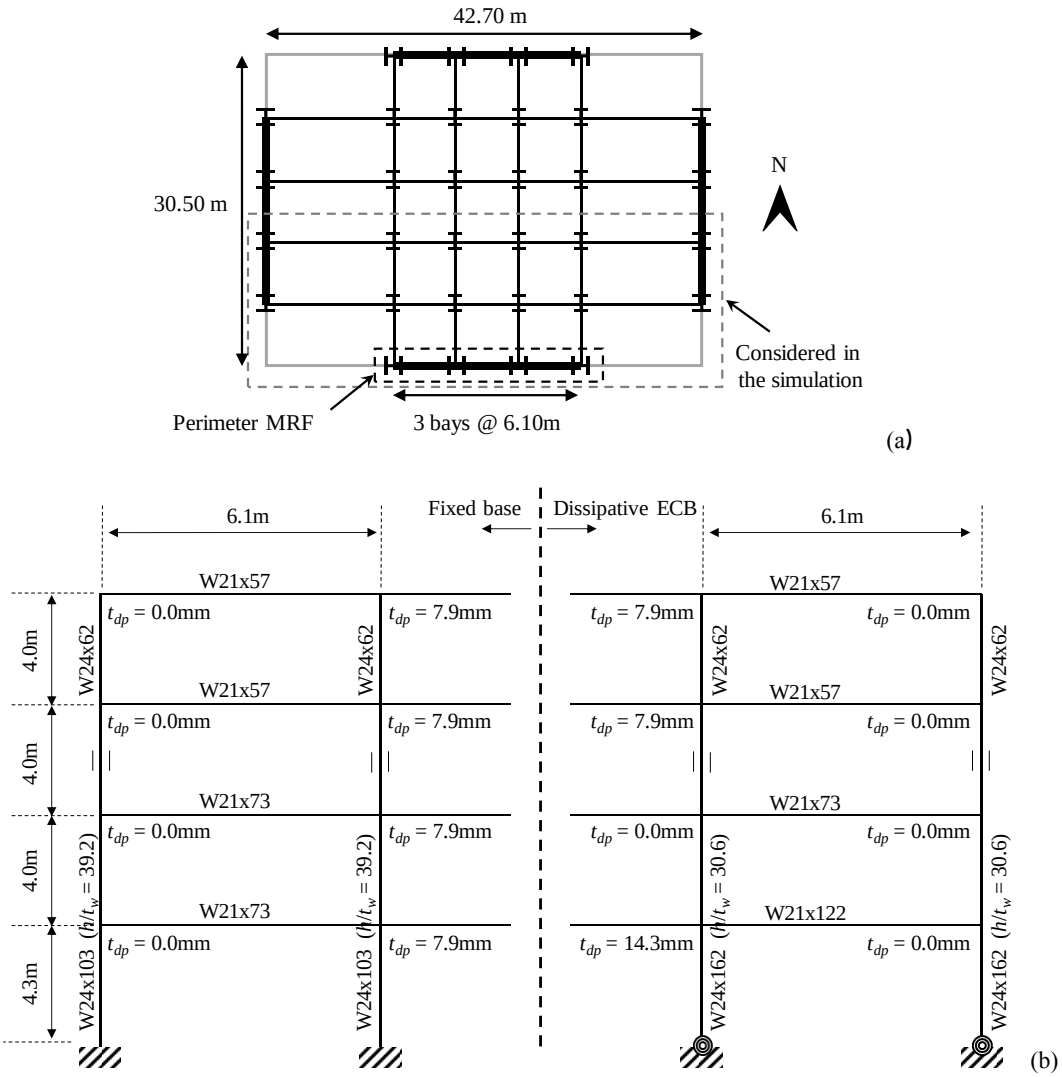


Figure 5. (a) Plan view and (b) elevation view of the case-study steel MRF building

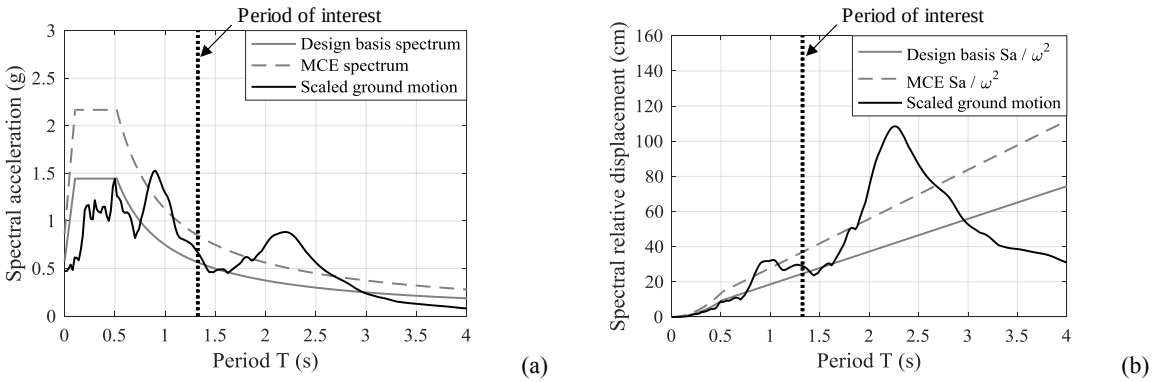


Figure 6. 5% damped elastic (a) absolute acceleration and (b) relative displacement response spectra of the adopted ground motion scaled by a factor of 1.1

The story-based (global) engineering demand parameters (EDPs) of interest involve the peak and residual story drift ratio (SDR) profiles obtained from NRHA. These are shown in figure 7. The peak SDRs along the steel MRF height shown in figure 7a are on the order of 3-4% in both cases. Referring to figure 7b, the residual SDR is found to be less than 0.25% in both MRFs. Although structural damage repairs may be expected, the chance of demolition due to residual story drifts is relatively low in both cases [37]. In summary, the simulation results suggest that the global EDPs do not differ by much.

Local EDPs in addition to the global ones are also evaluated. In particular, the steel column hysteretic response is examined with a particular emphasis on axial shortening. Figure 8a shows that the fixed column base exhibits severe flexural strength

deterioration under cyclic loading due to the relatively large number of inelastic cycles of the selected ground motion. On the other hand, the dissipative ECB connection absorbs the seismic energy through controlled yielding of the embedded column segment without experiencing any local geometric instabilities. While the energy dissipation in this case is smaller than the fixed column base case, there is no evident sign of cyclic deterioration in the examined case (see figure 8a). On the other hand, considerable column axial shortening is to be expected in the fixed base case. Since cumulative damage is approximated with a point hinge model, column axial shortening is estimated based on empirical equations developed by Elkady and Lignos [38]. On the contrary, since the dissipative ECB connection exhibits a stable hysteretic response, the empirical formulation proposed by MacRae [39] is employed. Both equations require the cumulative plastic rotation as well as the imposed gravity-induced axial load ratio along with the column's cross-sectional geometry. Figure 8b compares the estimated column axial shortening history obtained from the interior columns of each MRF subjected to the examined ground motion. In the fixed base case, the residual column axial shortening reaches 40mm. This may pose issues related to demolition due to vertical residual deformations since column axial shortening is not the same between columns of the same story and slab tilting may also be expected [40]. On the contrary, the axial shortening observed in the steel MRF with dissipative ECBs is less than 2mm. This demonstrates that the explored concept is promising and should be further explored to attenuate the expected column axial shortening in steel MRF columns in the aftermath of earthquakes.

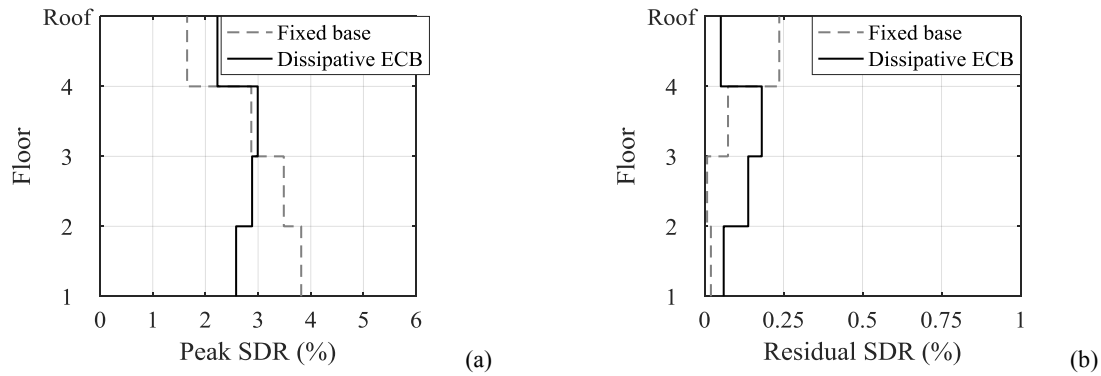


Figure 7. Global responses obtained from nonlinear response history analysis: (a) peak story drift ratio (SDR) profile and (b) residual story drift ratio (SDR) profile

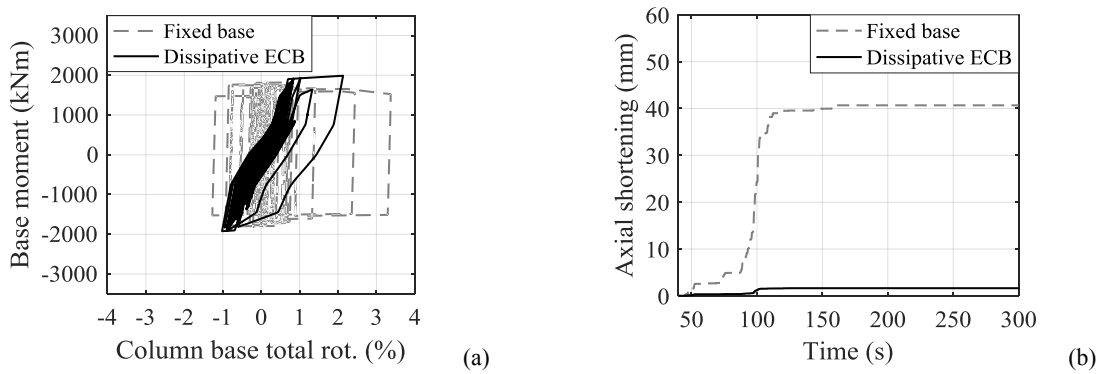


Figure 8. Interior column base responses obtained from nonlinear response history analysis: (a) base moment - column base total rotation relation (Column base total rotation = column bottom hinge rotation + dissipative ECB spring rotation (only for dissipative ECBs)) and (b) residual column axial shortening history estimated with equations from [38], [39]

5 SUMMARY

This paper explores concepts for mitigating residual axial shortening of wide-flange steel columns in moment-resisting frames (MRFs) by means of dissipative column base connections. While for exposed column bases (XCBs), this can be achieved through controlled anchor rod yielding, for embedded column bases (ECBs) the concept of rocking and sliding is explored. Numerical models replicating the flexural hysteretic behavior of both dissipative XCBs and ECBs were introduced. The potential impact of dissipative ECB connections on the steel MRF seismic response is investigated through nonlinear response history analyses. A 4-story steel MRF case study is employed for this purpose comprising dissipative ECB connections. This frame's seismic response is compared to the fixed-base one. A single long duration ground motion record is used to investigate the influence of inelastic loading cycles on the member's (and system's) seismic performance. The main observations from the exploratory study are summarized as follows:

1. Story-based (global) engineering demand parameter (EDP) responses (e.g., peak/residual story drift ratios) over the building height do not seem to be influenced from the incorporated column base assumption (fixed base or dissipative column base) as long as the corresponding drift limits per ASCE 7 are respected. In both MRFs, the residual story drift ratio was found to be less than 0.25%, indicating that the chance of building demolition due to residual lateral drift is relatively small for the examined cases.
2. On the other hand, the computed residual column axial shortening was nearly 40mm in the fixed base case. The dissipative ECB counterpart experienced minor axial contraction (less than 2mm) under the same ground motion.

Although inconclusive, this preliminary study suggests that dissipative column base connections may be the way forward to resolve a challenging problem associated with steel MRF column axial shortening in the aftermath of earthquakes. Detailed construction concepts validated to large-scale testing should be further developed and tested to realize such connections for further use in earthquake engineering practice. The authors are currently working towards this direction.

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