2019 SECED Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

EXPOSED COLUMN BASE CONNECTIONS FOR MINIMIZING EARTHQUAKE-INDUCED RESIDUAL DEFORMATIONS IN STEEL MOMENT-RESISTING FRAMES

Hiroyuki INAMASU[1], Albano DE CASTRO E SOUSA[2],
Gerard GÜELL BARTRINA[3] & Dimitrios G. LIGNOS[4]

Abstract: This paper proposes a new exposed column base (XCB) design concept for steel moment-resisting frames (MRFs) that promotes anchor rod yielding rather than plastic hinging at the bottom of the first story columns. A mechanics-based numerical model is first developed for simulating the complex XCB seismic behavior to further explore the design concept through simulations. Model validations with experimental data suggest that the proposed model is able to capture the hysteretic behavior of XCBs including yielding of each XCB component, contact and slip behavior, axial load – bending interaction, as well as their synergistic interaction. The new design concept is evaluated at the system-level by means of nonlinear response history analyses. The emphasis is placed on the earthquake-induced residual deformations of conventionally fixed base MRFs and those designed to promote anchor rod yielding. While global response quantities (e.g., peak story drift and residual lateral deformations) are nearly the same in both designs, local column base demands (e.g., residual column axial shortening) are considerably reduced when anchor rod yielding is promoted. From a repairability standpoint, the proposed concept shows promise and should be further explored in the future.

Introduction

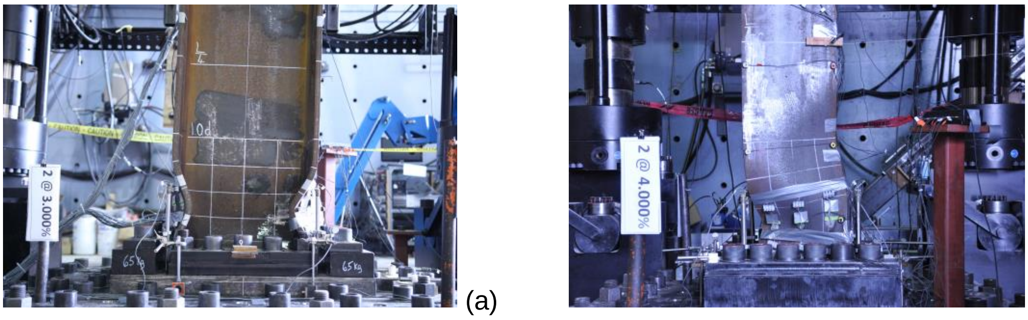
Exposed Column Base (XCB) connections are widely used in low-rise steel structures designed in seismic regions. XCBs comprise a base plate welded to a steel column, anchor rods that tie the base plate to the foundation, and a concrete or grout foundation on which the base plate is rested. When designed to be fixed, conventional XCB connections should remain elastic. The seismic action is dissipated through flexural yielding and/or local buckling forming at the base location of the first story columns.

Experiments and corroborating finite element simulations (e.g., Elkady and Lignos 2018a; b; Fogarty et al. 2017; Ozkula et al. 2017; Suzuki and Lignos 2015) suggest that first-story fixed base wide-flange steel columns comprising cross-sections near the seismic compactness limits of current code provisions (AISC 2016a), may exhibit coupled geometric instabilities (local and lateral torsional buckling) followed by residual axial shortening. Fig. 1 shows an example of residual axial shortening based on recent full-scale experiments (Elkady and Lignos 2018a). The column was imposed to a fully symmetric cyclic lateral loading protocol coupled with constant compressive axial load (P=0.2P_y, P_y is the column's axial strength). The resultant residual axial shortening due to local buckling was about 45mm (see Fig. 1a) and 110mm (see Fig. 1b) at 3% and 4% lateral drift demand. Residual axial shortening may be challenging to address from a repairability standpoint. While building-specific loss estimation studies (Hwang and Lignos 2017) in steel moment-resisting frames (MRFs) indicate that decisions related to demolition are largely impacted by lateral residual deformations, the influence of residual column axial shortening on losses due to demolition has been neglected. This may be a controlling aspect for demolition, particularly in cases that lateral residual deformations may be fairly minimal but steel columns still experience axial shortening due to inelastic cyclic straining. Construction methods should also evolve to prevent column axial shortening.

[1] Doctoral Assistant, Ecole Polytechnique Fédérale de Lausanne (Swiss Federal Institute of Technology, Lausanne), Lausanne, Switzerland, hiroyuki.inamasu@epfl.ch
[2] Postdoctoral Researcher, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[3] Former Master Student, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[4] Associate Professor, institution, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

The seismic performance of XCBs has been evaluated experimentally (Gomez et al. 2010; Takamatsu and Tamai 2005; Trautner et al. 2016, 2017; Yamanishi et al. 2009). Test results suggest that XCBs provide large plastic deformation capacity when anchor rod yielding is promoted. Moreover, it is easier to repair yielded anchor rods rather than repairing the steel column itself (Trautner et al. 2017). Although anchor rod yielding in XCBs has been investigated in prior studies (Cui et al. 2018; Trautner et al. 2019), there are notable gaps in terms of a coherent methodology to implement this design concept in practice.

This paper investigates the effect of anchor yielding on the seismic behavior of steel MRFs through numerical simulations. A mechanics-based XCB numerical model is first developed and validated with available test results. Two-story steel MRFs are then designed with the conventional and the new design concepts. The benefits of the anchor rod yielding are demonstrated by direct comparisons of local and global engineering demand parameters (EDPs) of interest to structural performance.



(a) (b)

Figure 1. Residual axial shortening of wide-flange steel column observed in 'specimen C3' (W24x146) tested by Elkady and Lignos (2018a): (a) front and (b) side views [at 2nd +3% and 2nd 4% column drift, respectively].

Exposed Column Base Model Development

Available XCB numerical models to facilitate system-level simulations (e.g., Rodas et al. 2016; Tanaka et al. 2005) are of phenomenological nature. Rodas et al. (2016) proposed a point plastic hinge model that mimics the cyclic behavior of XCBs through a set of empirical parameters calibrated to component test data. The model also assumes that the imposed axial load on the column remains constant, thereby ignoring the transient component of the axial load demands due to dynamic overturning effects. In a prior study, Tanaka et al. (2005) proposed a model that explicitly considers the base plate, the anchor rods, and the foundation. Axial load – bending interaction is also considered. However, base plate deformations and anchor rod strain hardening are neglected.

In this paper a generalized two-dimensional (2-D) mechanics-based numerical model of XCBs is proposed. The model does not require calibration to component test data. Fig. 2 shows an overview of the model. It comprises elements for each XCB component. The primary assumptions of the model are as follows: (a) anchor rods are placed in two rows (one row for each side) outside the column depth; (b) plastic deformation of the base plate is limited; (c) grout or concrete foundation remains elastic. Detailed modeling of the anchors depends on the employed column erection procedure. In particular, the presence of leveling nuts changes the force transfer mechanism in XCB connections (Gomez et al. 2010; Trautner et al. 2016) and, therefore, necessitates different modeling strategies.

In brief, anchor rods are modeled with a circular fiber section assigned to force-based elements with 5 integration points. Prior experiments suggest that the bonding between anchors and the concrete foundation is either negligible (Gomez et al. 2010; Kanvinde et al. 2013) or fairly limited (Trautner et al. 2017). Therefore, it is assumed that the entire anchor rod length contributes to the anchor deformation. Depending on the threading length or the presence of leveling nuts, several segments may be used along the anchor rod's length. Fig. 2b illustrates the material assignments and the element division depending on the corresponding XCB case. Slip and contact behavior between the anchor rods and the base plate or the leveling nuts is considered by appropriate material laws. In particular, three different material laws are used: (a) Voce-Chaboche material (noted as 'Chaboche' in Fig 2b) that includes combined kinematic/isotropic hardening law (Lemaitre and Chaboche 1994; Voce 1948); (b) Chaboche-No-Compression (Chaboche-NC) material that is a combination of 'Chaboche' and rigid elastic no-compression law in series; and (c) Chaboche-NC-Contact material that is a combination of 'Chaboche-NC' and rigid elastic no-tension in parallel. 'Chaboche-NC' mimics the slip behavior of the anchors while 'Chaboche-NC-Contact' simulates the slip behavior in the tensile strain domain as well as the contact behavior in the compressive strain domain. The former is used for the XCB anchors without leveling nuts. If these are adopted, the latter is used for the anchor segments between leveling and top nuts. Minimum root diameter of threads, $D_{min.}$ and nominal diameter (unthreaded diameter), $D_{maj.}$ are adopted for the threaded and the unthreaded parts, respectively.

The base plate is modeled with a displacement-based element with a fiber section (outside the column depth) or an elastic beam-column element with rigid material (inside the column depth). The base plate is assumed to be rigid in between the two column flanges. Outside the column flanges, the 'Chaboche' material law is employed. The yield lines are assumed to be perpendicular to the base plate length in the proposed modeling approach.

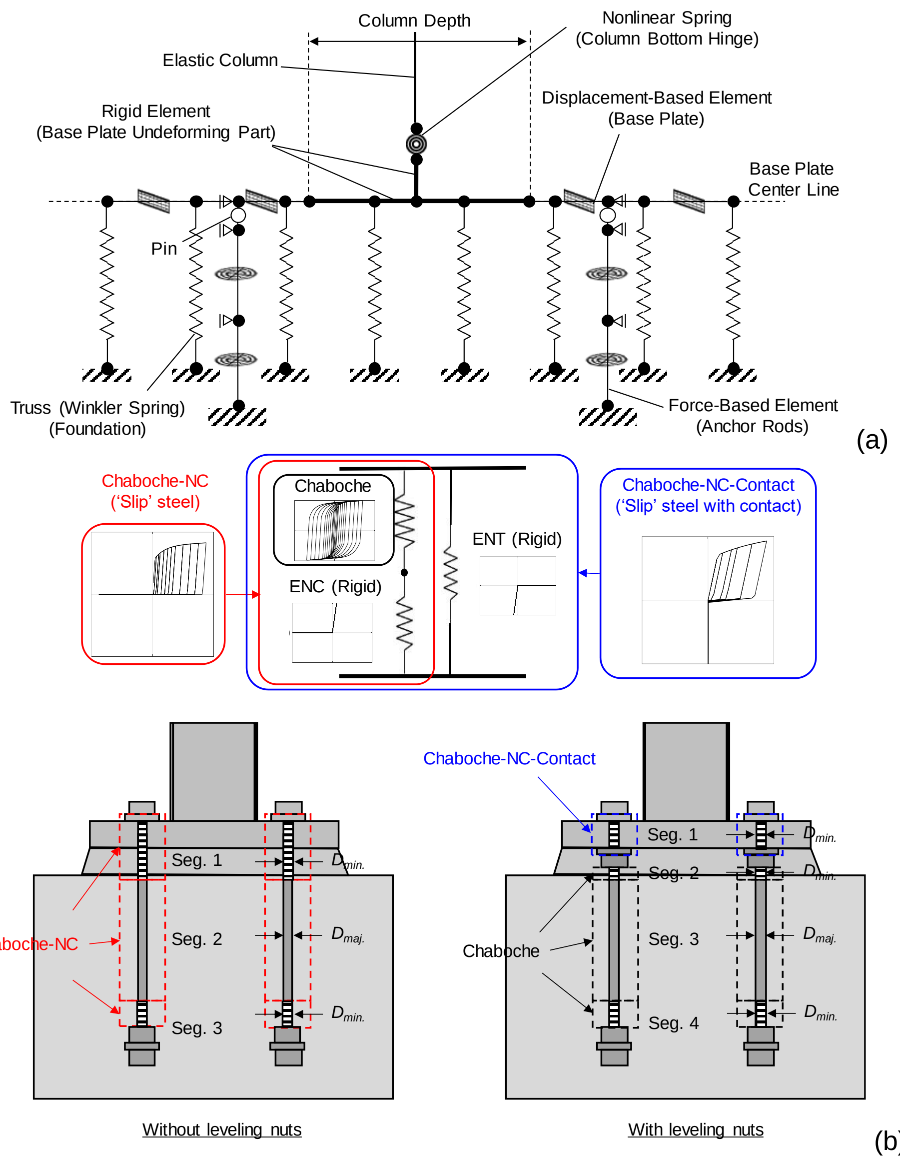


Figure 2. Schematic Illustration of XCB Model: (a) modeling of each component; and (b) material assignment for each segment of an anchor rod.

The grout or concrete foundation is modeled by a number of truss elements equally spaced along the base plate length (so-called 'Winkler springs') with elastic no-tension (ENT) material. The use of the ENT material allows for column base uplifting. The bearing stiffness of the foundation is determined as discussed in prior studies (Steenhuis et al. 2000) and current practice (CEN 2005).

The proposed model and associated material models have been implemented in the open-source simulation platform OpenSees (McKenna 1997).

Preliminary Model Validations

The proposed model is evaluated with available experimental data. Two of the validation studies are shown herein. Tests conducted by Yamanishi et al. (2009) (specimen S-Var) and Gomez et al. (2010) (specimen 5) are selected for this purpose.

Specimen S-Var (Yamanishi et al. 2009) comprises a hollow structural section (HSS) column (STKR400 200x200x12mm). The anchors are ABR400 4-M16 (2 anchors per each side) with a nominal yield stress, f_y=215~235MPa, the base plate is 400x400x50mm made of SS400 (f_y=205~245MPa). This rests on a steel beam foundation. In this case, yielding is purely concentrated within the anchor rods. The specimen is subjected to reversed cyclic symmetric lateral loading (in displacement control) coupled with varying axial load demands. The specimen did not have leveling nuts.

The material model parameters for the Chaboche model are obtained from a steel material database developed by Sousa and Lignos (2018). Winkler springs are considered to have rigid compressive stiffness since a steel beam was used as a foundation block in this case. Twelve Winkler springs are employed for this purpose.

Figure 3a compares the simulated and measured base moment (moment acting at the column center on the base plate top surface level) – base plate rotation (inclination of the base plate). Overall, the proposed model captures well the hysteretic behavior of the XCB including the axial load – moment interaction. Slight differences in the flexural stiffness observed during the initial loading and unloading are attributed to the flexibility of the steel beam foundation (Yamanishi et al. 2009).

Specimen 5 of (Gomez et al. 2010) comprises a wide flange W8x48 steel column (ASTM A992 Gr. 50, f_y=345MPa), ASTM F1554 Gr. 105 4-D19mm anchors (2 anchors in each side) and a 356x356x25.4mm base plate made of A36 steel (f_y=250MPa). The base plate rests on a grout layer on top of the concrete foundation positioned flat with leveling nuts. The specimen is subjected to cyclic lateral loading (in displacement control) coupled with a constant axial load (411kN). Anchor rods are designed to yield first followed by base plate yielding. For the most part, the numerical modeling approach is identical to Yamanishi et al. (2009)'s S-Var specimen, except for the Winkler springs' stiffness and the leveling nut details.

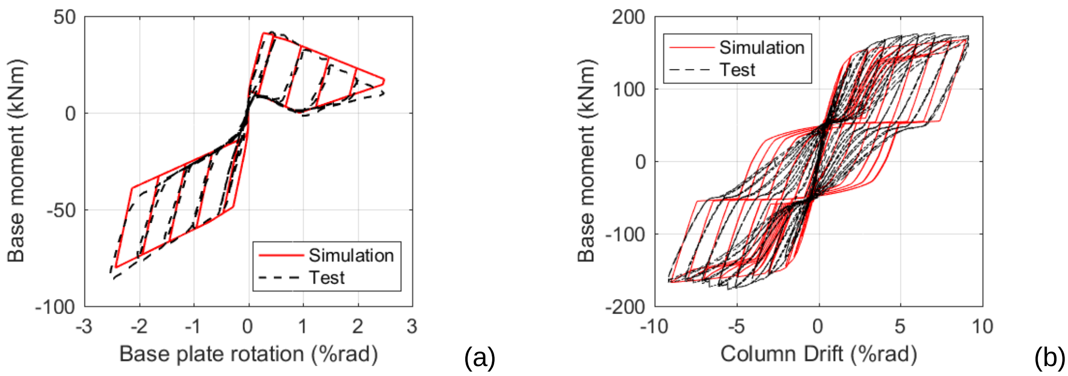


Figure 3. Comparison in moment-rotation response between proposed model and test data: (a) Yamanishi et al. (2009) specimen 'S-Var' and (b) Gomez et al. (2010) specimen 5.

Figure 3b compares the simulated and measured base moment – column drift (column top lateral displacement divided by the column height). Four different yielding mechanisms are evident in this test, namely: (1) yielding and hardening of the threaded part as well as the shank (unthreaded part) of the anchor rods; (2) yielding and hardening of the base plate; (3) pinching caused by the gap created between the leveling and top nuts due to the plastic deformation of the corresponding anchor segments; and (4) an additional flexural resistance due to the axial load (Gomez et al. 2010). Their interaction indicates a complex hysteretic behavior as shown in Fig. 3b. The proposed model exhibits a reasonably good agreement to the experimental results, as indicated by the same figure. The observed pinching was found to be strongly dependent on the amount of plastic deformation between the nuts mentioned in point (3) above. This is influenced by the plastic deformation of the anchor segments below the leveling nuts as well as the base plate deformation.

All-in-all, considering the above comparisons, the proposed model is deemed to be appropriate for system level studies to further examine the influence of anchor rod yielding on the overall steel MRF seismic performance. This is discussed in the subsequent sections.

Steel Moment Resisting Frame Designs

Two different designs are conducted for a 2-story steel frame building with perimeter 3-bay steel MRFs. These are designed as special moment frames according to the American design standards (AISC 2016a; b; c; ASCE 2016). The first one assumes a fixed base (termed conventional); and the second one assumes intentional anchor rod yielding. Fully-restrained reduced beam section (RBS) connections are adopted. The building plan view is shown in Fig. 4. It is consistent with that used in prior studies (Elkady and Lignos 2015; NIST 2010). The structure is assumed to be located in urban California (seismic design category: D, site class: D). Fig. 5 shows the design spectrum (DBE level) of this site as well as that corresponding to a maximum considered earthquake (MCE:1.5xDBE) according to ASCE (2016). Steel beams and columns are designed with ASTM A992 Gr. 50 steel (f_y=345MPa). The final member sizes are summarized in Table 1 for both designs. The member sizes for the intentional anchor yielding case are slightly different than those in the fixed base case since the flexibility of the XCB connections is explicitly considered in the design phase. The gravity-induced axial loads, P_g sustained by the columns are 3~4% of P_y in the fixed base frame and 2~3% in the anchor yielding base frame. The gravity system is explicitly considered. Its columns and beams are W14x90 and W24x55 with ASTM A992 Gr. 50 steel, respectively. They are connected through conventional shear tab connections.

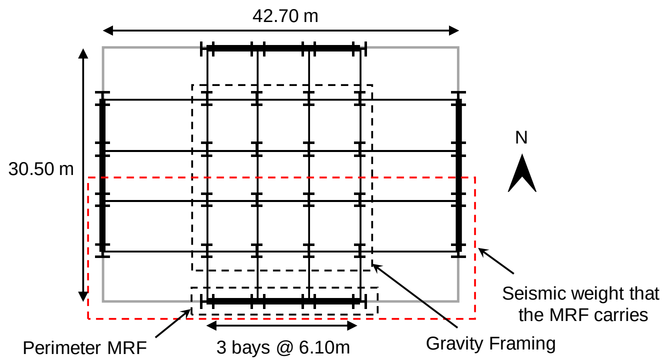


Figure 4. Plan view of the building.

The XCBs are designed in accordance with ACI (2014); AISC (2016a); ASCE (2016); Fisher and Kloiber (2006). In both cases, a shear lug is adopted to transfer the shear force to the foundation. In the fixed base case, in order to keep XCB elastic under seismic loading, the flexural demands are increased to the maximum moment that the column can sustain (Lignos et al. 2019). In the anchor yielding case, XCBs are designed to achieve a similar flexural strength as the fixed-base columns. Consequently, the column size is merely larger than that of the fixed-base case. Both anchor rods are designed with ASTM F1554 Gr. 105 (f_y=724MPa). The corresponding base plates are made of ASTM A572 Gr. 50 steel (f_y=345MPa). The concrete foundation is designed with a compressive strength f_c' = 30MPa. The dimensions of each XCB component are summarized in Table 2. For simplicity, anchor rods are assumed to be threaded throughout their length. Columns are assumed to be erected without leveling nuts in this design example.

Column Base	Story	Beam Size	Column size	Doubler plate thickness (Ext./Int.)
Fixed	2 (4.0 m)	W21x93	W21x111 (h/t_w = 34.1)	0.0/14.3 mm
	1 (4.2 m)	W21x62	W21x111 (h/t_w = 34.1)	0.0/7.9 mm
Anchor yielding	2 (4.0 m)	W21x93	W24x146 (h/t_w = 33.2)	0.0/7.9 mm
	1 (4.2 m)	W21x62	W24x146 (h/t_w = 33.2)	0.0/3.2 mm

Table 1. Member sizes of the SMF for each design concept (h/t_w: web local slenderness ratio)

Column Base	Anchor rods			Base plate
	Total num.	D_{maj}	***Effective length***	***Length* x *Width* x *Thickness***
Fixed	8	50.8 mm (2”)	690 mm	1100x720x139.7 mm (*t* = 5 1/2")
Anchor yielding	8	34.9 mm (1 3/8”)	710 mm	1000x500x120.7 mm (*t* = 4 3/4")

Table 2. Dimensions of XCB components for each design concept

Frame Modeling Approach and Nonlinear Simulations

A 2-D nonlinear model representation of the steel MRF in the E-W loading direction of the 2-story building is developed in OpenSees. Beams and columns are modeled with nonlinear rotational springs placed at the member-ends. The modified Ibarra-Medina-Krawinkler (Ibarra et al. 2005) deterioration model with bilinear hysteretic response is assigned to these springs. The model parameters for the steel columns and beams with RBS are computed as suggested by Lignos et al. (2019); Lignos and Krawinkler (2011), respectively. The model proposed by Gupta and Krawinkler (1998) is used to simulate potential inelastic behavior within the beam-to-column web panel zone. The gravity framing action is considered in the model by adding an equivalent gravity frame (EGF) as discussed in Elkady and Lignos (2015). Column bases are either fixed (for the fixed base case) or detailed with the developed XCB model (for anchor yielding base case). Rayleigh damping is incorporated in the 2-D frame model as discussed in Zareian and Medina (2010). Two percent damping ratio is assumed at the first and second modes of each frame model. A negligible amount of stiffness proportional damping is also applied to Winkler springs and beam-column elements for anchors to improve the overall numerical stability of the nonlinear simulations. Regarding this matter, it is always attested that the resultant damping forces are negligible throughout the analysis (less than 1% of the maximum element force). The first mode natural period is 0.66s and 0.59s for the fixed base and anchor yielding cases, respectively, based on standard eigenvalue analysis.

The proposed design concept is explored by means of nonlinear response history analysis with a ground motion record from the Tohoku earthquake (EQ) 2011 in Japan. The record is obtained from the Japan Meteorological Agency (2018). In particular, the North South (NS) component data measured at the ‘Namiemachi Kiyohashi (Namie)‘ station in Fukushima prefecture is employed. The acceleration record is filtered with a 4th order Butterworth filter with band pass from 0.1Hz to 0.4/dt Hz (dt is sampling interval of the record). This filtering corrects the distortion in ground velocity and displacement history obtained from integration of an unfiltered acceleration record all the while keeping the same spectral shape. This record has a significant duration of 92s (t = 51s ~ 143s) based on the definition of the time interval over which 5% - 95% of the Arias intensity is attained (Foschaar et al. 2012). This duration is relatively long (Trifunac and Brady 1975) and may cause considerable cyclic deterioration in strength and stiffness of the respective structural components of the steel MRF. Fig. 5 shows the 5% damped elastic response spectrum of the ground motion record scaled by a factor of two. The ground motion intensity at the spectral accelerations of interest (marked with a dashed line) may be considered equivalent to a MCE.

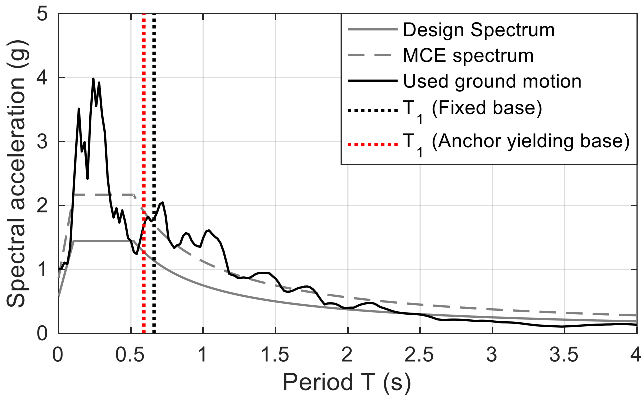
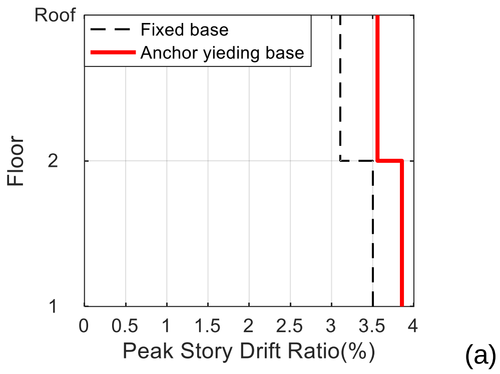


Figure 5. Absolute acceleration response spectra from ASCE (2016) and Namie-NS record from Tohoku EQ in Japan in 2011.

Representative results by means of nonlinear response history analyses of the two considered MRFs are summarized in Figs. 6-8. Referring to Fig. 6a, while both structures experience fairly large peak story drift ratios (fixed base: 3.5%; and anchor rod yielding: 3.9%), structural collapse did not occur in both cases. The slightly larger peak story drift ratio in the anchor-yielding-base frame may be attributed to the pinching behavior of the XCB connections. Referring to Fig. 6b, the maximum lateral residual story drift over the steel MRF height was about 0.5%.



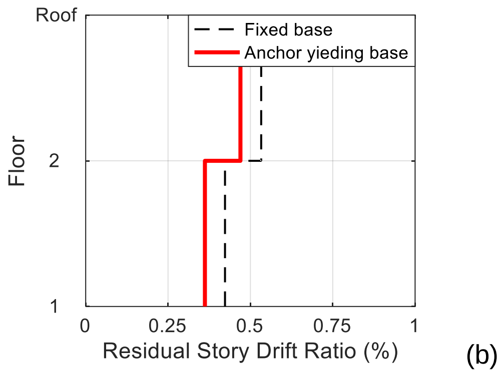


Figure 6. Global EDPs obtained from NRHA: (a) peak and (b) residual story drift profiles.

Figures 7 show the comparison of the base moment – column base total rotation (column bottom hinge rotation + XCB base plate rotation (for anchor yielding base case only) responses for the interior and exterior column bases, respectively. While column plastic hinging dominates the response of the fixed-base columns, anchor rod yielding dominates the response of the second design. In this case, column plastic deformation is prevented, and the anchor rods do not exhibit strength deterioration. Moreover, the corresponding peak axial strain in the anchors does not exceed 4% in all the examined cases. Referring to Fig. 7a, the plastic rotation accumulation in the conventional design case causes appreciable flexural strength degradation of the first story columns.

Figure 8a shows the first column bottom hinge rotation history obtained from one of the interior columns. Most notably, the accumulated plastic deformation caused considerable column residual axial shortening. Figure 8b shows the column axial shortening history for the same ground motion record. The shortening is computed based on the Elkady and Lignos (2018b) empirical formula given the corresponding cumulative plastic rotation of the column, its web local slenderness ratio, and the imposed gravity-induced axial load ratio. The residual axial shortening attained about 45 mm in the fixed-base case (same amount as the one shown in Fig. 1a) due to damage concentration in the bottom of the column. In stark contrast, the seismic design with intentional anchor rod yielding indicated virtually zero axial shortening for the same ground motion record. From a repairability standpoint, it is considerably more challenging to restore a column with axial shortening than without. In terms of deciding whether the building should be demolished or not this fact can be primordial, given that its lateral residual deformation is not significant (almost at 0.5% as shown in Fig. 6b) and, therefore, not a determining factor.

Summary and Observations

This paper suggested a new column base design concept in steel moment-resisting frames that promotes anchor rod yielding rather than column flexural yielding. A numerical model that simulates the behavior of the exposed column base (XCB) connections including the axial load – moment interaction was developed for the system level simulation. The developed XCB model was validated with available experiments. Nonlinear response history analysis of the MRFs with a single long duration ground motion record corresponding to MCE level is performed in order to assess the benefit of the new column base design concept. The main findings are summarized as follows:

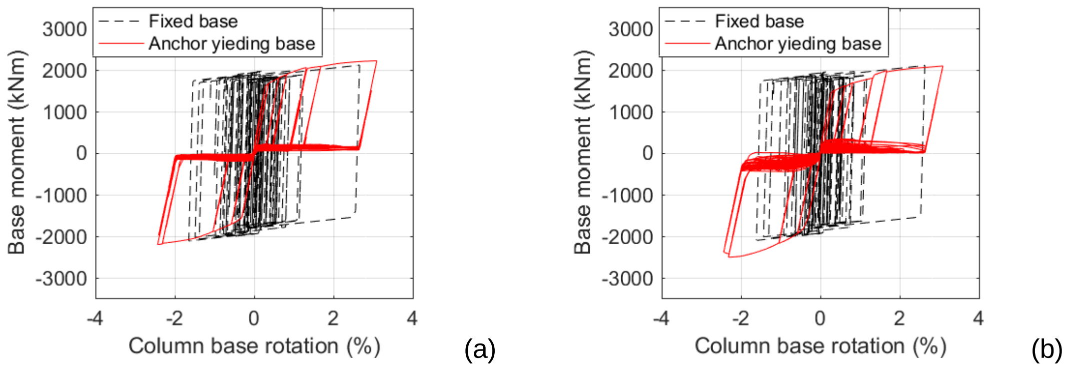


Figure 7. (a) Interior and (b) Exterior column base responses obtained from NRHA.

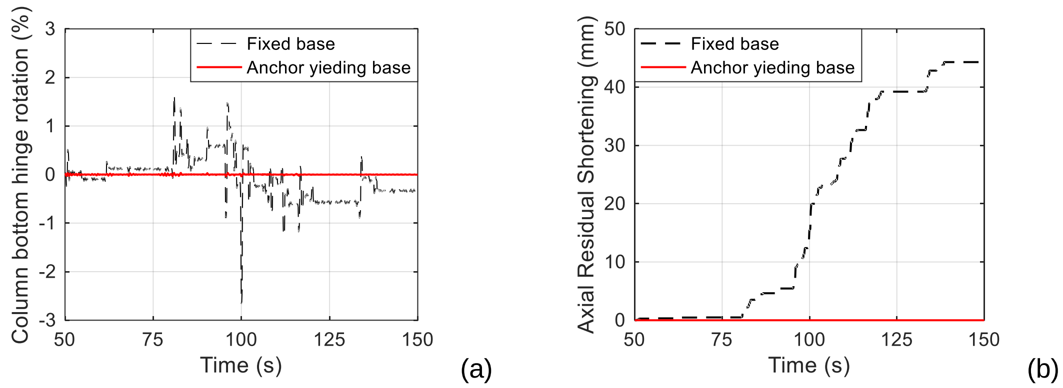


Figure 8. (a) Interior column hinge rotation history and (b) residual axial shortening history computed based on (a).

1. The proposed XCB model was able to replicate the complex behavior of XCB connections exhibiting different failure mechanisms. Explicit modeling of each component of an XCB allows for the proper simulation of the synergistic failure mode interactions.
2. In the frame designed with the new column base design concept, dissipative mechanisms were successfully shifted to the anchor rods from the column. Although the local response in the column bases was dominated by pinching, there was no significant difference in global responses such as the peak story drift ratios along the steel MRF height.
3. In the fixed-base frame residual column axial shortening was found to be considerable (45 mm). Although the building response did not suggest demolition due to lateral residual deformations, the building may still be demolished due to severe residual column axial shortening. On the contrary, in the new design concept, the column axial shortening was nearly zero while the lateral drift response of the steel MRF (both maximum and residual) were almost identical to the fixed-base steel MRF.

Acknowledgement

This study is based on work supported by the Swiss National Science Foundation (Award No. 200021_169248). Financial support for the second and third authors was also provided through internal EPFL funding. The financial support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of sponsors.

References

ACI. (2014). *Building Code Requirements for Structural Concrete and Commentary. ACI 318-14*. American Concrete Institute.

AISC. (2016a). *Seismic Provisions for Structural Steel Buildings. ANSI/AISC 341-16*. American Institute of Steel Construction.

AISC. (2016b). *Specification for Structural Steel Buildings. ANSI/AISC 360-16*. American Institute of Steel Construction.

AISC. (2016c). *Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications. ANSI/AISC 358-16*. American Institute of Steel Construction.

ASCE. (2016). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures. ASCE/SEI 7-16*. American Society of Civil Engineers.

CEN. (2005). "Eurocode 3 Design of Steel Structures Part 1-8: Design of Joints."

Cui, Y., Wang, F., and Yamada, S. (2018). "Effect of Column Base Behavior on Seismic Performance of Multi-Story Steel Moment Resisting Frames." *International Journal of Structural Stability and Dynamics*, 19(01), 1940007.

Elkady, A., and Lignos, D. G. (2015). "Effect of Gravity Framing on the Overstrength and Collapse Capacity of Steel Frame Buildings with Perimeter Special Moment Frames." *Earthquake Engineering & Structural Dynamics*, 44(8), 1289–1307.

Elkady, A., and Lignos, D. G. (2018a). "Full-Scale Testing of Deep Wide-Flange Steel Columns under Multiaxis Cyclic Loading: Loading Sequence, Boundary Effects, and Lateral Stability Bracing Force Demands." *Journal of Structural Engineering*, 144(2), 04017189.

Elkady, A., and Lignos, D. G. (2018b). "Improved Seismic Design and Nonlinear Modeling Recommendations for Wide-Flange Steel Columns." *Journal of Structural Engineering*, 144(9), 04018162.

Fisher, J., and Kloiber, L. (2006). "Base Plate and Anchor Rod Design, Steel Design Guide 1, 2nd edition."

Fogarty, J., Wu, T. Y., and El-Tawil, S. (2017). "Collapse Response and Design of Deep Steel Columns Subjected to Lateral Displacement." *Journal of Structural Engineering*, 143(9), 04017130.

Foschaar, J. C., Baker, J. W., and Deierlein, G. G. (2012). "Preliminary Assessment of Ground Motion Duration Effects on Structural Collapse." *Proceedings of the 15th World Conference on Earthquake Engineering (WCEE)*, Lisbon, Portugal.

Gomez, I., Deierlein, G., and Kanvinde, A. (2010). *Exposed Column Base Connections Subjected to Axial Compression and Flexure. Final Report Presented to American Institute of Steel Construction.* Chicago.

Gupta, A., and Krawinkler, H. (1998). "Seismic Demands for the Performance Evaluation of Steel Moment Resisting Frame Structures." Ph.D. Thesis, Stanford University.

Hwang, S.-H., and Lignos, D. G. (2017). "Earthquake-induced loss assessment of steel frame buildings with special moment frames designed in highly seismic regions." *Earthquake Engineering & Structural Dynamics*, 46(13), 2141–2162.

Ibarra, L. F., Medina, R. A., and Krawinkler, H. (2005). "Hysteretic Models that Incorporate Strength and Stiffness Deterioration." *Earthquake Engineering & Structural Dynamics*, 34(12), 1489–1511.

Japan Meteorological Agency. (2018). "Japan Meteorological Agency Website." Available at: https://www.data.jma.go.jp/svd/eqev/data/kyoshin/jishin/110311_tohokuchiho-taiheiyouoki/index.html (Accessed 05/04/2019).

Kanvinde, A. M., Jordan, S. J., and Cooke, R. J. (2013). "Exposed Column Base Plate Connections in Moment Frames — Simulations and Behavioral Insights." *Journal of Constructional Steel Research*, 84, 82–93.

Lemaitre, J., and Chaboche, J.-L. (1994). *Mechanics of Solid Materials*. Cambridge university press.

Lignos, D. G., Hartloper, A. R., Elkady, A. M. A., Deierlein, G. G., and Hamburger, R. (2019). "Proposed Updates to the ASCE 41 Nonlinear Modeling Recommendations for Wide-Flange Steel Columns in Support of Performance-based Seismic Engineering (In press)." *Journal of Structural Engineering*.

Lignos, D. G., and Krawinkler, H. (2011). "Deterioration Modeling of Steel Components in Support of Collapse Prediction of Steel Moment Frames under Earthquake Loading." *Journal of Structural Engineering*, 137(11), 1291–1302.

McKenna, F. (1997). "Object Oriented Finite Element Programming Frameworks for Analysis, Algorithms and Parallel Computing." Ph.D. Thesis, University of California, Berkeley.

NIST. (2010). *Evaluation of the FEMA P695 Methodology for Quantification of Building Seismic Performance Factors*. NEHRP consultations Joint Venture.

Ozkula, G., Harris, J., and Uang, C.-M. (2017). “Observations from Cyclic Tests on Deep, Wide-Flange Beam-Columns.” *Engineering Journal*, 1, 45–59.

Rodas, P. T., Zareian, F., and Kanvinde, A. (2016). “Hysteretic Model for Exposed Column-Base Connections.” *Journal of Structural Engineering*, 142(12), 04016137.

Sousa, A., and Lignos, D. G. (2018). *On the Inverse Problem of Classic Nonlinear Plasticity Models -An Application to Cyclically Loaded Structural Steels-*. Ecole Polytechique Federal de Lausanne, RESSLab.

Steenhuis, C. M., Wald, F., Stark, J. W. B., Sokol, Z., and Taylor, J. C. (2000). “Resistance and Stiffness of Concrete in Compression and Base Plate in Bending.” *JCSR in printing*.

Suzuki, Y., and Lignos, D. G. (2015). “Large Scale Collapse Experiments of Wide Flange Steel Beam-Columns.” *Proceedings of the 8th International Conference on Behavior of Steel Structures in Seismic Areas (STESSA)*, Shanghai, China.

Takamatsu, T., and Tamai, H. (2005). “Non-Slip-Type Restoring Force Characteristics of an Exposed-Type Column Base.” *Journal of Constructional Steel Research*, 61(7), 942–961.

Tanaka, H., Mitani, I., Shimamura, Y., and Itoh, M. (2005). “Elasto-Plastic Behavior of Steel Frame with Exposed Type Column Base Subjected to Variable Axial Force.” *Steel Construction Engineering (In Japanese)*, 12(45), 171–184.

Trautner, C. A., Hutchinson, T., Grosser, P. R., and Silva, J. F. (2017). “Investigation of Steel Column–Baseplate Connection Details Incorporating Ductile Anchors.” *Journal of Structural Engineering*, 143(8), 04017074.

Trautner, C. A., Hutchinson Tara C., Grosser, P. R., and Silva, J. F. (2016). “Effects of Detailing on the Cyclic Behavior of Steel Baseplate Connections Designed to Promote Anchor Yielding.” *Journal of Structural Engineering*, 142(2), 04015117.

Trautner, C., Hutchinson, T., Grosser, P., Piccinin, R., and Silva, J. (2019). “Shake Table Testing of a Miniature Steel Building with Ductile-Anchor, Uplifting-Column Base Connections for Improved Seismic Performance.” *Earthquake Engineering & Structural Dynamics*, 48(2), 173–187.

Trifunac, M. D., and Brady, A. G. (1975). “A Study on the Duration of Strong Earthquake Ground Motion.” *Bulletin of the Seismological Society of America*, 65(3), 581–626.

Voce, E. (1948). “The Relationship between Stress and Strain for Homogeneous Deformation.” *Journal of the Institute of Metals*, 74, 537–562.

Yamanishi, T., Takamatsu, T., Tamai, H., Matsumura, T., and Matsuo, A. (2009). “Resistance Mechanism of Non-Slip-Type Exposed Column-Base under Tensile Variable Axial-Force.” *Journal of Structural and Construction Engineering (Transactions of AIJ) (In Japanese)*, 74(642), 1495–1502.

Zareian, F., and Medina, R. A. (2010). “A Practical Method for Proper Modeling of Structural Damping in Inelastic Plane Structural Systems.” *Computers & Structures*, 88(1), 45–53.