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Seismic Stability of Multi-Tiered Ordinary Concentrically-Braced Frames

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Abstract

Multi-tiered braced frames (MT-BFs) are created when a tall single-story braced bay is divided into multiple bracing panels over the height, with no diaphragms or out-of-plane column supports between the base and roof. Due to the unique conditions in MT-BFs, during nonlinear seismic response, they are susceptible to column instability due to combined axial force and bending moment. The present research is using numerical simulations to investigate the seismic response of multi-tiered ordinary concentrically-braced frames (MT-OCBFs), which are designed with a relatively simple procedure and are expected to provide limited inelastic deformation capacity. The baseline for the study is the previous version of the AISC *Seismic Provisions* (AISC 341-10), which require column design for an amplified axial demand. The newer AISC *Seismic Provisions* (AISC 341-16), which are based on a limited initial evaluation to develop the multi-tiered OCBF requirements, stipulate that MT-OCBF columns be designed for an additional amplified axial demand to approximately account for moment. This approach is now being more comprehensively studied, and the interaction effects of axial force, in-plane moment and out-of-plane moment are being thoroughly assessed. This paper presents the results from nonlinear static (pushover) analysis of a subset of the prototype frames. Concentration of inelastic deformations and column buckling were observed in some of the baseline designs, while the newer provisions allow for a more even distribution of inelastic demand over the frame height. For OCBFs, a simple but effective design approach is desired so that drift concentration in a single tier is limited and column stability is maintained, even without employing a rigorous capacity-based procedure.

1. Introduction

Steel braced frames are commonly used as lateral force resisting systems for tall single-story steel buildings that have applications in industrial warehouses, airplane hangars, and performing art centers. In such braced frames, the single-story may be divided into multiple bracing panels with intermediate struts, with no diaphragms or column out-of-plane support at the strut levels between the base and roof level, to form multi-tiered braced frames (MT-BFs). MT-BFs can be designed with various brace configurations such as X, split-X, V (chevron), and inverted-V. Two examples of brace configurations in MT-BFs are shown in Fig. 1.

In MT-BFs, the brace lengths are reduced compared to tall frames with a single panel, and smaller braces can be used. Therefore, MT-BFs are a practical and economical solution for tall single-story buildings as well as for tall stories in multi-story buildings. MT-BFs are particularly advantageous

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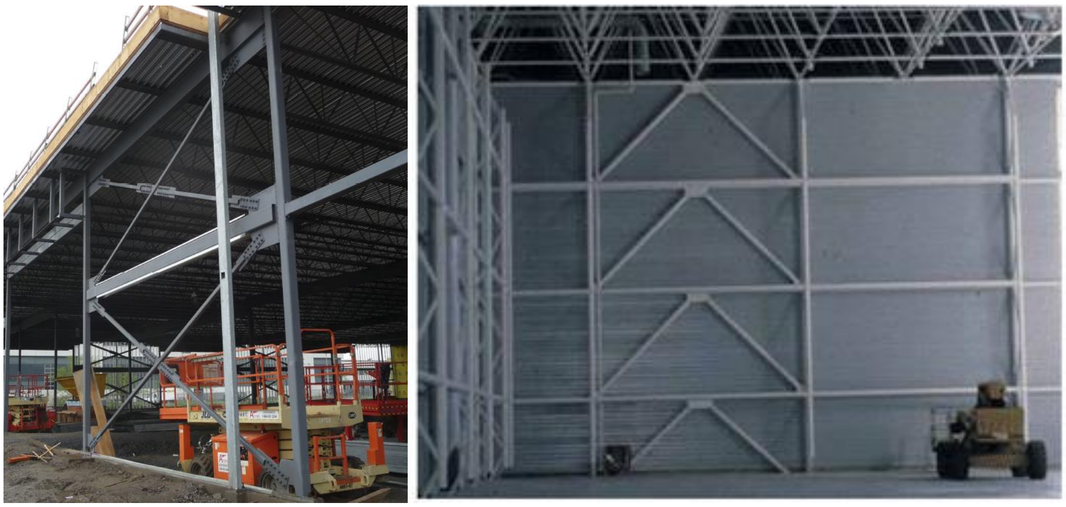
in seismic applications since the reduced braces lengths make it easier to meet slenderness requirements imposed for ductile seismic design. In addition, the smaller brace sizes result in lower forces in other components of the frame such as connections, columns, and beams that are capacity designed.



(a) (b)

Figure 1. MT-BFs in single-story, steel buildings (Imanpour et al. 2016) (a) 2-tier X bracing (b) 4-tier chevron bracing (Imanpour and Tremblay 2016).

The MT-BF configuration gives rise to a unique condition in which flexural demands are imposed on the columns along with axial force such that the columns are susceptible to instability. Prior research has focused primarily on multi-tiered special concentrically braced frames (MT-SCBFs) and is discussed in Section 1.1. A similar investigation is needed for multi-tiered ordinary concentrically-braced frames (MT-OCBFs). This paper presents results from an ongoing study on the seismic performance of MT-OCBFs. The design process for OCBFs is relatively simple, with no rigorous capacity design requirements since these systems are intended to provide limited inelastic deformation capacity. The results from a nonlinear static (pushover) analysis on a subset (X-braced configuration) of prototype frames developed for this study is presented here. Frame designs in accordance with the previous version of the AISC *Seismic Provisions*, AISC 341-10 (AISC 2010a), are used as a baseline for this study, and the results are compared and contrasted with design as per the new version of the AISC *Seismic Provisions*, AISC 341-16 (AISC 2016). The primary focus of the results presented is column stability under the combination of axial force, in-plane moment and out-of-plane moment, which is directly related to brace inelastic axial response and tier drift distribution.

1.1 Behavior of MT-BFs

Seismic response of concentrically-braced frames (CBFs) is primarily determined by brace inelastic axial response. However, in MT-BFs, significant column flexure can be generated by unbalanced horizontal forces that develop at strut levels due to differences in tier shear strength. Unlike multi-story braced frames, the mass of the structure is concentrated at the top of the frame (story), so inertial forces do not develop at the strut levels and the unbalanced horizontal forces must be resisted by column flexure. Even though nominal tier shear strengths are typically equal, differences in adjacent tier strengths do develop during inelastic seismic response. Consequently, inelastic deformation demand can be concentrated in the critical tier where brace tension yielding is initiated. This not only imposes high ductility demand on the braces that can lead to brace fracture, but also prevents tension yielding of braces in adjacent tiers and makes the columns vulnerable to instability due to excessive flexural demands. A parametric study that considered various frame heights, number of tiers and tier height ratios to investigate the seismic response of MT-SCBFs, shows that column in-plane flexural buckling, due to axial and flexural demands, is the primary failure mode. Further, the in-plane demands can be exacerbated by out-of-plane demands due to lack of out-of-plane support at the tier levels (Imanpour et al. 2016).

1.2 Research Need

Studies based on two- and four-tiered SCBFs have proposed design methods aimed at preventing column failure through redistribution of inelastic demands, limiting deformation in the braces to prevent fracture, and controlling tier drift concentration (Imanpour et al. 2014, 2016). The proposed design procedure, validated by nonlinear static and dynamic analyses, imposes minimum column strength and in-plane stiffness requirements for satisfactory seismic performance. MT-OCBFs require a simplified design procedure to consider the additional demands imposed on the columns due to brace inelastic response, but without a rigorous capacity-based procedure.

2. Design Framework

This section provides a brief overview of the AISC *Seismic Provisions* that are used for designing the various components of an OCBF. AISC 341-10 does not have specific design provisions for the multi-tiered configuration, whereas the newer AISC 341-16 details the design procedure for MT-BFs. Thus, for design in accordance with AISC 341-10, the requirements used are simply those prescribed for multi-story OCBFs.

2.1 Overview of AISC *Seismic Provisions*

As mentioned previously, OCBFs are intended to exhibit limited ductility and therefore, a rigorous capacity design procedure is not employed. As per AISC 341-10, a simple approach is to amplify the seismic load effects by the overstrength factor of the system (Ω_0) to account for additional demands in the columns and connections. Since there is no specific strength requirement for the struts, for the purposes of this study, the struts are designed to resist the full frame seismic base shear in compression. The newer AISC 341-16 imposes an additional amplification of 1.5 on the horizontal earthquake effects considered for the columns, struts, and the connections (1.5 Ω_0). The column design is further enhanced by the application of out-of-plane notional loads in order to consider bending moment demands induced by second order and geometric imperfection effects. These requirements are summarized in Table 1 in the context of the X-braced configuration. Additional requirements may apply for other brace configurations.

Table 1. Summary of AISC *Seismic Provisions* for MT-OCBFs

Member / Component	AISC 341-10*	AISC 341-16
Brace	• Moderately ductile • Required strength based on the load effect of appropriate load combinations	• Moderately ductile • Required strength based on the load effect of appropriate load combinations
Column	• Required strength based on load effect of appropriate load combinations with amplified seismic loads and vertical earthquake effect	• Required strength based on load effect of appropriate load combinations with overstrength seismic loads and an additional 1.5 multiplier for the horizontal earthquake effect • Out-of-plane horizontal notional loads at each tier equal to at least 0.006 times the vertical load effect of the compression brace at the tier level
Strut	• No specific requirement	• Required strength based on appropriate load combinations, including overstrength seismic load effect and an additional 1.5 multiplier for the horizontal earthquake effect
Connection	• Required strength based on amplified seismic load effect**	• Required strength based on the overstrength seismic load effect with a multiplier of 1.5 for the horizontal earthquake effect**

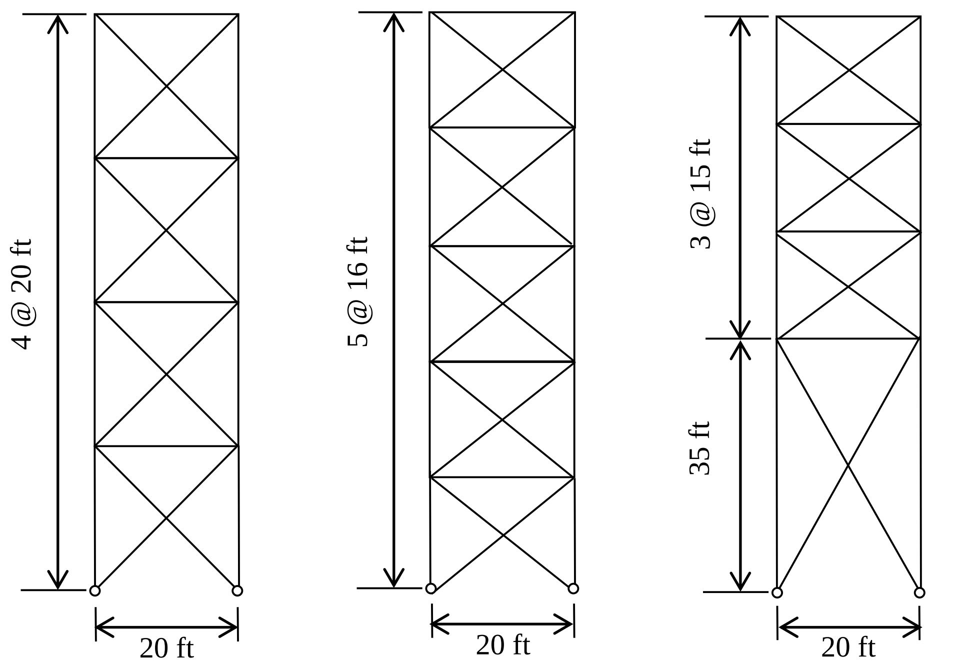
*No specific MT-BF requirements
**Exceptions are noted in the AISC *Seismic Provisions*

2.2 Seismic Design of MT-OCBFs

The frames presented in this study are used to resist lateral loads in an 80 ft tall, single-story industrial steel building with a 460 ft x 180 ft plan and 180 ft long roof trusses spanning the width of the building. Four MT-BFs, each with a bay width of 20 ft, are considered in each of the two orthogonal directions. The geometry of the frames considered in this study is shown in Fig. 2.

All frames are designed as OCBFs with response modification coefficient R = 3.25, deflection amplification factor C_d = 3.25, and system overstrength factor Ω_o = 2.0. In addition, all frames are designed in accordance with ASCE 7-10 (ASCE 2010). Members are designed as per the provisions of AISC 360-10 Specification (AISC 2010b), and AISC 341-10 or AISC 341-16. Seismic design of OCBF-4X-U^3 is discussed here in more detail.

The gravity loads in the structure include a roof dead load of 25 psf and exterior wall weight of 25 psf. Live loads are ignored in this study. For determining the seismic design loads, the structure is assumed to be located in coastal California, on site class D. Thus, the design spectral acceleration parameters are S_{DS} =1.0g and S_{D1} = 0.6g. The building is assigned an importance of 1.0 and the equivalent lateral force procedure is used to compute the seismic base shear. A 10% amplification is also considered to approximately account for accidental eccentricity between centers of mass and stiffness. The design fundamental period, C_uT_a, for the frames is 0.74 seconds since the actual (calculated) fundamental periods were all greater than C_uT_a, and the seismic response coefficient C_s = 0.249. The seismic weight of the building and design base shear for each frame is equal to 3350 kips and 230 kips, respectively.



OCBF-4X-U OCBF-5X-U OCBF-4X-NU

Figure 2. Geometry of MT-OCBFs.

The braces are designed to resist the combined compressive effect of gravity and seismic loads. An effective length factor of 0.45 on the overall workpoint length is considered in design, and HSS sections with material nominal yield strength F_y = 50 ksi are used (ASTM A1085). For OCBF-4X-U, HSS5x5x3/8 sections were selected for the braces.

The columns are designed to resist the axial loads induced by gravity and seismic loads, including the vertical earthquake effect. The horizontal earthquake effects are appropriately amplified and the out-of-plane bending moment is considered for the design in accordance with AISC 341-16. The columns are continuous over the height of the frame and are oriented for weak-axis bending in-plane. Columns are assumed to be pinned at the base with in-plane lateral bracing and torsional restraints assumed to be provided by the struts, also oriented for weak-axis bending in-plane. Effective length factors of 0.80 and 0.79 are considered for in-plane and out-of-plane buckling, respectively, and W sections with material nominal yield strength F_y = 50 ksi are used (ASTM A992). For OCBF2010-4X-U and OCBF2016-4X-U, W27x178 and W30x261 sections were selected, respectively.

The struts are proportioned to resist the design base shear with appropriate amplification where required. The struts are oriented with their webs in the horizontal plane. W sections with material nominal yield strength F_y = 50 ksi are used (ASTM A992). For OCBF-4X-U, W8x48 and W12x87 sections were selected as per AISC 341-10 and AISC 341-16, respectively.

Based on ASCE 7-10, story drifts were calculated using seismic loads obtained from the computed period of the structure from an eigenvalue analysis. The design story drift ratio of OCBF2010-4X-U was checked for the design basis earthquake (DBE), $C_d\Delta_e/h$ =0.76% and verified to be less than the allowable story drift ratio of 2% prescribed in ASCE 7-10. In addition, the story drift ratio under the maximum considered earthquake (MCE) was estimated as 50% larger than the design drift ratio, $1.5C_d\Delta_e/h$= 1.14 %. The computed period and story drift at DBE and MCE are summarized in Table 2 for all frames. Frame member designs as per both AISC 341-10 and AISC 341-16 are presented.

Table 2. Member sizes and design parameters.

Parameter	OCBF10-4X-U	OCBF16-4X-U	OCBF10-5X-U	OCBF16-5X-U	OCBF10-4X-NU	OCBF16-4X-NU
Computed Period (s)	1.069	0.982	1.092	1.005	0.997	0.946
Story Drift (%) DBE MCE	 0.76 1.14	 0.71 1.06	 0.78 1.17	 0.73 1.10	 0.72 1.08	 0.68 1.03
Brace	HSS5x5x3/8	HSS5x5x3/8	HSS5x5x5/16	HSS5x5x5/16	HSS7x7x1/2 & HSS5x5x5/16	HSS7x7x1/2 & HSS5x5x5/16
Column	W27x178	W30x261	W27x178	W30x261	W30x235	W36x302
Strut	W8x48	W12x87	W8x48	W12x87	W8x48	W12x87

3. Numerical Model

A three-dimensional numerical model was created using the *OpenSees* (McKenna and Fenves 2006) simulation platform. A schematic of the model is shown in Fig. 3. The braces and columns are modeled using non-linear force beam-column elements with fiber discretization of the respective cross-sections to capture the inelastic buckling response of the members. The uniaxial Giuffré-Menegotto-Pinto (Steel02) material model is used to simulate the kinematic and isotropic strain-hardening as well as the Bauschinger effect. The nominal yield strength F_y = 50 ksi and expected yield strength R_yF_y = 70 ksi is assigned for the column and brace elements, respectively. A reduced expected yield strength of $0.95R_yF_y$ = 66.5 ksi is used for the braces of the first tier of frames with identical tier heights to account for inherent material variability, and to initiate brace yielding in the first tier in which the column segment carries the maximum axial load. In addition, a residual stress pattern with $F_{residual}$ = $0.3F_y$ for compression is employed for the columns (Galambos and Ketter 1958). Elastic beam-column elements are used to model the roof beam and the struts of the braced frame, as well as a leaning column to account for P-Δ effects from gravity loads. Bi-directional initial out-of-straightness, with a half-sine profile and an amplitude of 1/1000 of the unsupported length of the member, is specified for the braced frame columns. Only out-of-plane initial imperfections are specified for the braces. Pinned bases are simulated for the columns by restraining the torsional and the three translational degrees of freedom. The out-of-plane translational degree of freedom is restrained at the column tops. The roof beam and struts are pin-connected to the columns for in-plane flexure. Stiff elastic beam-column elements, with ten times the stiffness of the adjacent element, are used at the brace, column, and struts ends to capture the connection size effects and to force inelastic deformations outside the gusset plate region. Nonlinear zero-length rotational springs are included at the transition between the rigid end zone and brace element (physical end of the brace members) to simulate the out-of-plane flexural response of the gusset plates (Hsiao et al. 2013). Identical rotational springs are included in the middle gusset plate to connect the discontinuous brace segments with the stiff elastic beam-column elements considered for the middle gusset plate. Stiff beam-column elements are included for the continuous brace segments at the intersection points. Point masses representing the seismic weight of the structure are included at the tops of the braced frame columns. Concentrated tributary roof dead loads are applied to the braced frame and the leaning column.

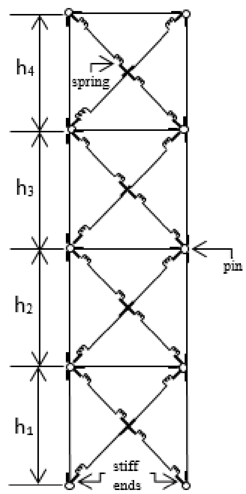


Figure 3. Schematic of numerical model in *OpenSees.*

4. Nonlinear Static Analysis

In MT-BFs, the seismic mass of the building is concentrated at the roof level (top of the single story), thus inertial forces only develop at the roof level. Due to this, a nonlinear static (pushover) analysis can be used to provide insight into the expected dynamic response under the first large inelastic displacement cycle during a ground motion record, when brace inelastic response may cause concentration of inelastic drift in a tier and trigger column failure. The results from a pushover analysis of OCBF10-4X-U and OCBF16-4X-U are discussed in detail. Results for the remaining frames are presented briefly, and a comparative discussion of frame responses is included.

4.1 Frame Case Study

In this section, the results from the pushover analysis of OCBF10-4X-U and OCBF16-4X-U are discussed. Fig. 4a shows the pushover curve (base shear vs. story drift) for OCBF10-4X-U.

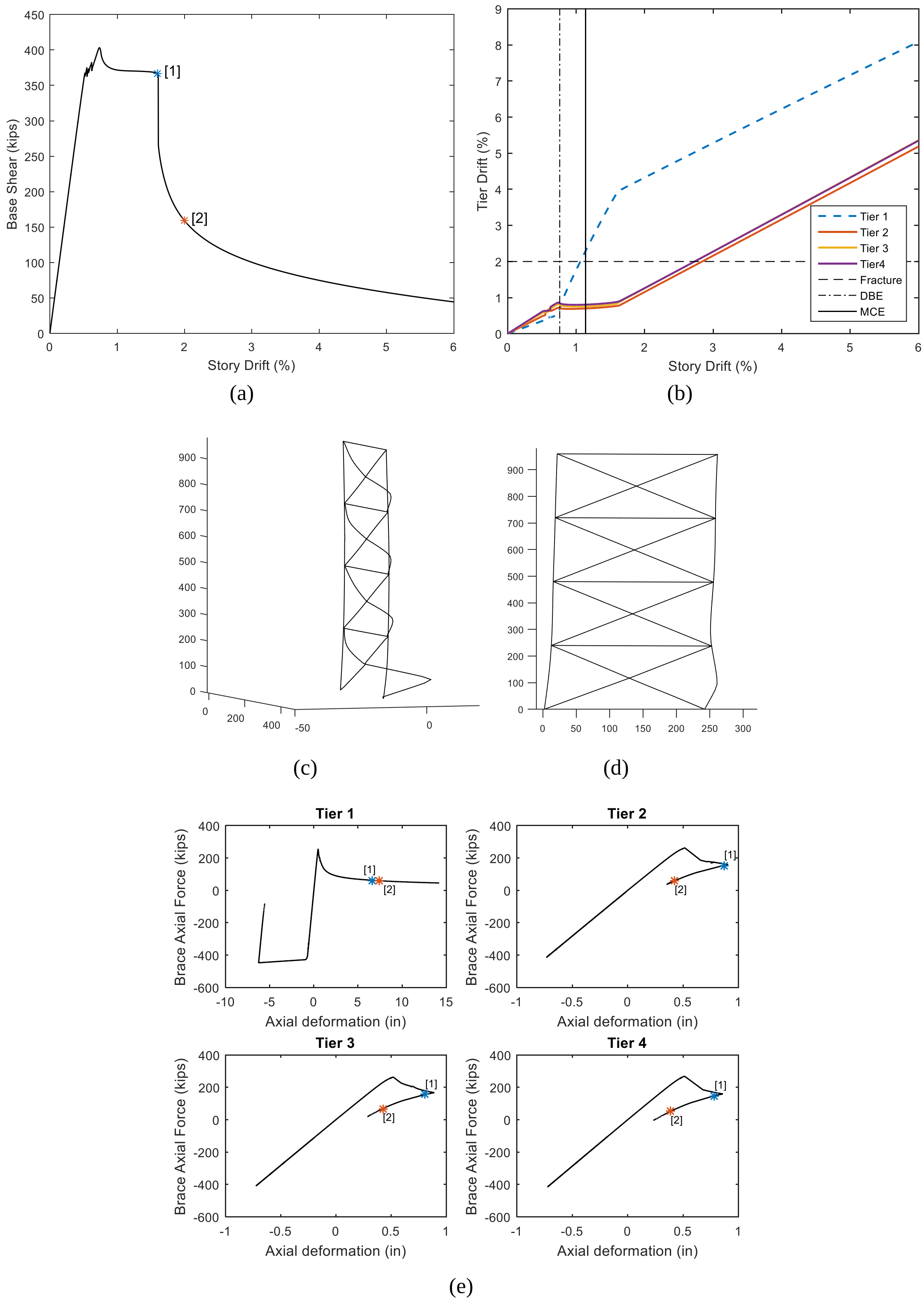


Figure 4. Response of OCBF10-4X-U (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Profile view of displaced shape at point [1]; (d) Elevation view of displaced shape at point [2]; (e) Brace response (positive indicates compression and axial shortening).

Linear elastic response was seen up to 0.52% story drift when buckling of the compression brace in Tier 1 was initiated. The maximum base shear resisted by the frame was reached at a story drift of 0.74% when yielding of the Tier 1 tension brace was initiated. Following this, the lateral load resisted by the frame dropped as the Tier 1 compression brace strength degraded in the post-buckling region. As seen in Fig. 4b, the tier drifts at the first and other tiers also diverged at the same story drift value, up to which, negligible difference was observed. The difference in tier drifts increased steadily up to approximately 1.6% story drift, at which point, the imposed flexural demands, in conjunction with the axial force on the compression column, initiated column buckling. This corresponds to point [1] marked on the pushover curve. The drifts in the non-critical tiers were almost identical, indicating rigid body motion of the frame as column buckling occurred. At the estimated design story drift (for the DBE), all tier drifts were below 2%. However, at the estimated MCE story drift, the drift in Tier 1 exceeded 2% of the tier height. This is cause for concern since large tier drifts (greater than 2%) can lead to premature brace fracture. The displaced shape shown in Fig. 4c clearly indicates large out-of-plane deformations in the braces at column buckling. At the ASCE 7-10 imposed allowable story drift of 2%, the lateral load resisted by the frame was about 2.5 times less than the maximum resisted lateral load of 403 kips. This is point [2] on the pushover curve. The displaced shape corresponding to point [2], Fig. 4d, shows the plastic hinge that formed in the column segment of the first tier. The overall brace force vs. deformation response is shown in Fig. 4e. The lateral resistance of the frame reduced rapidly with column buckling. The post-buckling behavior of the first tier compression brace and unloading of braces in adjacent tiers at points [1] and [2] is also marked.

Fig. 5a shows the pushover curve, with point [1] indicating 2% story drift, for OCBF16-4X-U. The frame exhibited linear elastic response up to 0.46% story drift. At this point, buckling of the Tier 1 compression brace occurred. Buckling of compression braces in the adjacent tiers followed in close succession. The frame reached its maximum lateral load resistance of 412 kips at a story drift of 0.63%, when yielding of Tier 1 tension brace was observed. As opposed to the AISC 341-10 design, tension yielding was triggered in the braces of the adjacent tiers, with small reductions in base shear as the yielding progressed over the frame height. The redistribution of inelastic demand in the frame is evident in Fig. 5b. The plot shows that the tier drifts were similar up to a story drift of 0.6% when Tier 1 drift deviated. The drifts in the upper tiers followed closely up to 1.1 % story drift when Tier 2 drift deviated. The same trend was seen in the other tiers. At the estimated design story drift (for the DBE), all tier drifts were below 2%. Large Tier 1 drifts were reached before the estimated MCE story drift was reached; however, it is worth noting that Tier 2 drift increased soon after, thus indicating some potential for alleviation of the inelastic deformation demands imposed on the Tier 1 braces. Similar observations were made for the upper tiers. In-plane column buckling was not observed in this frame as confirmed by the displaced shapes shown in Fig. 5c and 5d. The braces exhibited out-of-plane buckling over the full height and all braces reached the post-buckling range as shown in Fig. 5e.

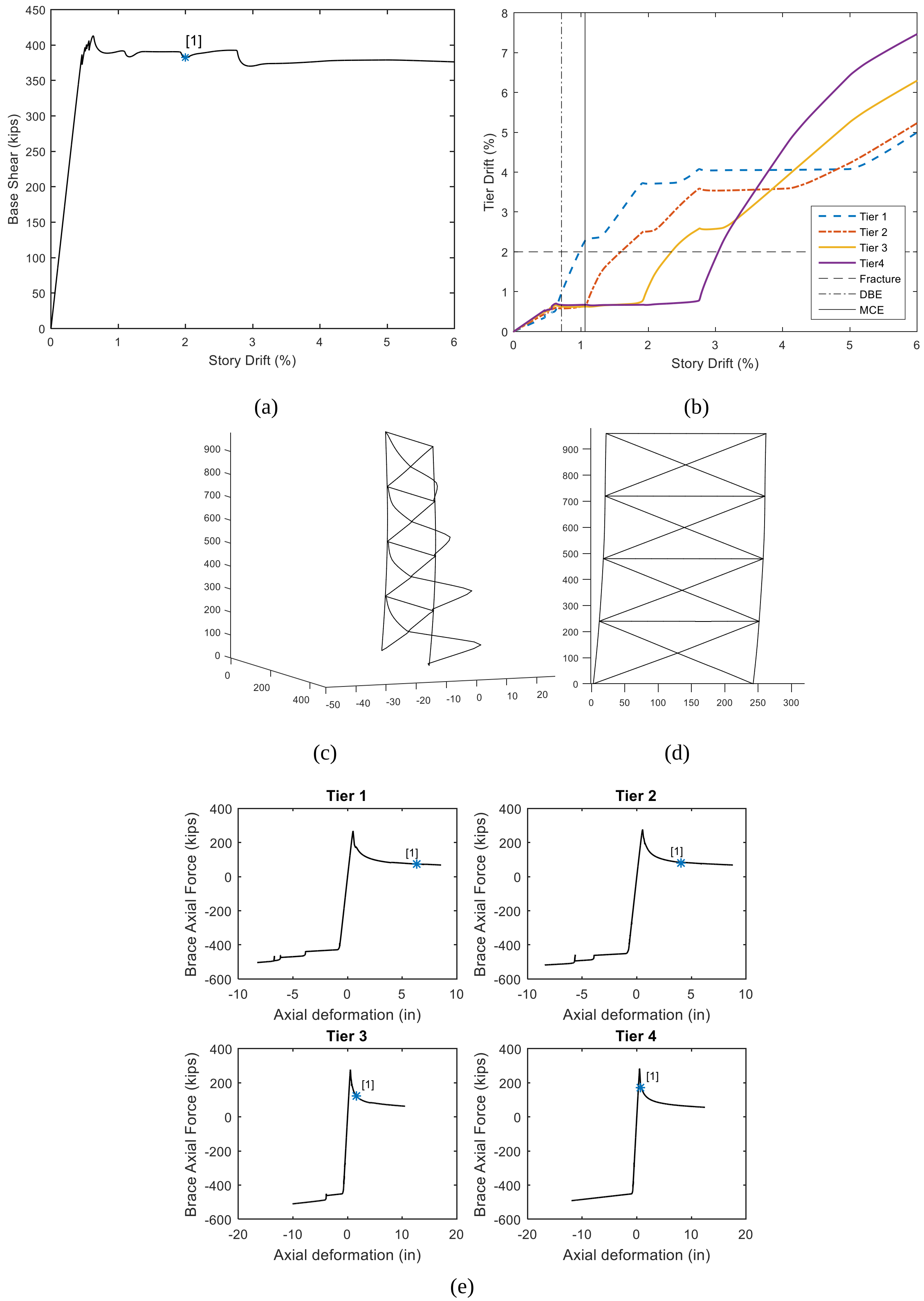


Figure 5. Response of OCBF16-4X-U (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Profile view of displaced shape at point [1]; (d) Elevation view of displaced shape at point [1]; (e) Brace response (positive indicates compression and axial shortening).

A comparison of the pushover results of the two frame designs confirms that – for this frame – the AISC 341-16 design provisions address the issue of column buckling and prevent significant reduction of the lateral resistance that follows column buckling. The new design also allows for more even redistribution of inelastic demand through brace buckling and yielding in all the tiers. However, nonlinear dynamic analyses are also needed for a comprehensive assessment. Further, since low-cycle fatigue failure of the braces is not considered in a monotonic static analysis, a more thorough investigation of cyclic response is required. Results from analyses on additional frame configurations must also be considered.

4.2 Comparative Study of Frame Response

The seismic response of the remaining two frames, designed as per both AISC 341-10 and AISC 341-16, is briefly summarized with plots provided in the Appendix, Sections 7.1 and 7.2, respectively. The columns of OCBF10-5X-U and OCBF16-5X-U are identical to those of their corresponding four tier frames, but the five tier configuration resulted in a smaller in-plane unbraced length for the column. This reduced the susceptibility of the column to in-plane bending. The compression braces showed post-buckling behavior after progressive buckling was observed over the frame height. Thus, the inelastic demand was redistributed over the full height which protected the column from developing excessive bending moments. For the OCBF-4X-NU frames, brace buckling was first initiated in the upper tiers as opposed to the bottom tier in uniform tier frames. At a story drift of 2%, the braces of the upper tiers exhibited their post-buckling response, while the Tier 1 compression brace remained elastic. No tension yielding behavior was observed in Tier 1. This was because a larger HSS 7x7x1/2 section was selected for the Tier 1 braces to satisfy slenderness limits for *moderately ductile members* as per the AISC *Seismic Provisions*. A significant difference was observed in the column response in OCBF10-4X-NU and OCBF16-4X-NU. In the former, column buckling was initiated at 2.6% story drift due to the brace buckling response described previously. In contrast, OCBF16-4X-NU, which had larger columns due to the additional axial force amplification in design, did not exhibit column buckling until 4.4% story drift. This comparison illustrates the general effectiveness of the AISC 341-16 enhanced column design requirement, but it also shows that column buckling may still occur, albeit at very large story drift. Further investigation is needed to evaluate the effectiveness of the AISC 341-16 MT-BF requirements.

5. Conclusions and Future Work

This paper presented the results from nonlinear static (pushover) analysis of multi-tiered ordinary concentrically braced frames (X-braced configuration) designed according to both AISC 341-10 and AISC 341-16 *Seismic Provisions*. The responses of three frame geometries were compared in terms of concentration of tier drifts, brace axial response, and column buckling due to the combined effects of axial loads and bi-axial bending moment. Significant column bending was observed in some MT-OCBFs designed as per AISC 341-10, while this issue was successfully addressed in AISC 341-16. Large tier drift concentration was observed in the former design considerations, while the inelastic demand was relatively well distributed in the enhanced column design of the latter. However, the MT-OCBF design approach in AISC 341-16 should be more thoroughly evaluated with nonlinear response history analysis. In addition, future work in this study will consider additional frame designs with various heights, tier height ratios, and brace configurations to develop a comprehensive assessment of the seismic stability and performance of MT-OCBFs.

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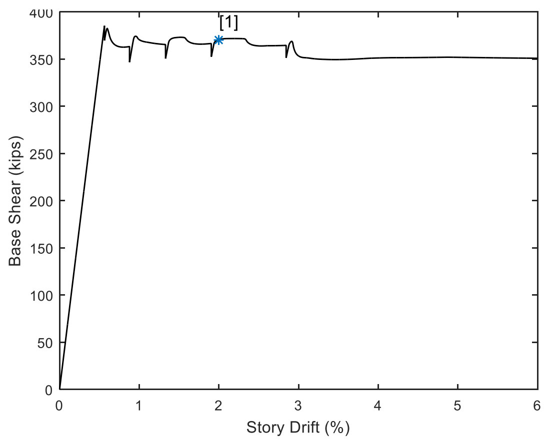
7. Appendix

7.1 Results for OCBF-5X-U



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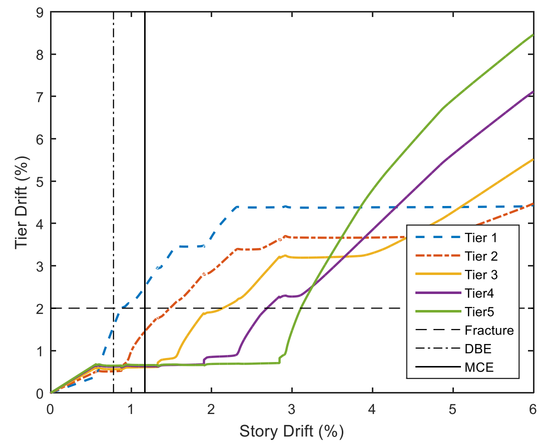

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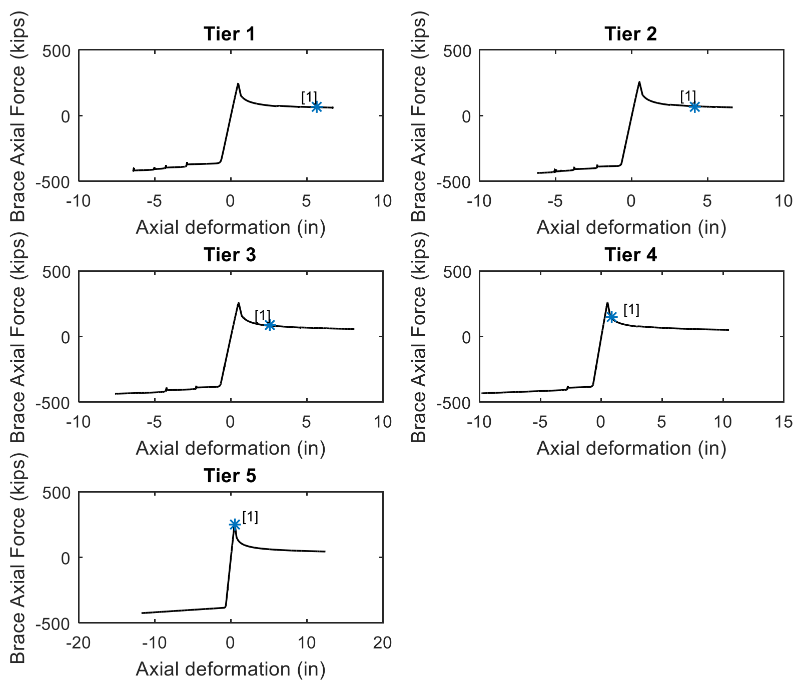

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Figure 6. Response of OCBF10-5X-U (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Brace response (positive indicates compression and axial shortening).

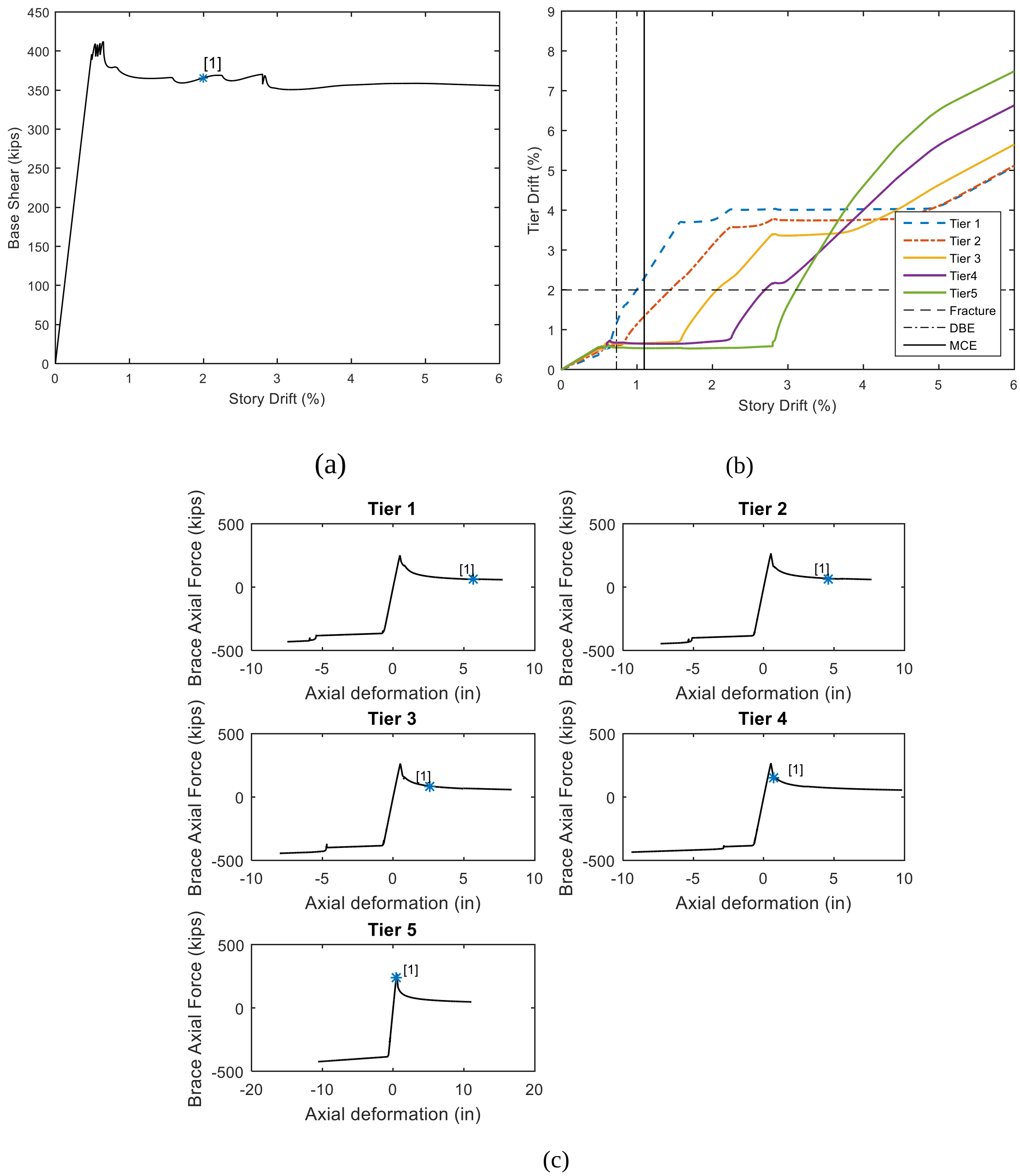
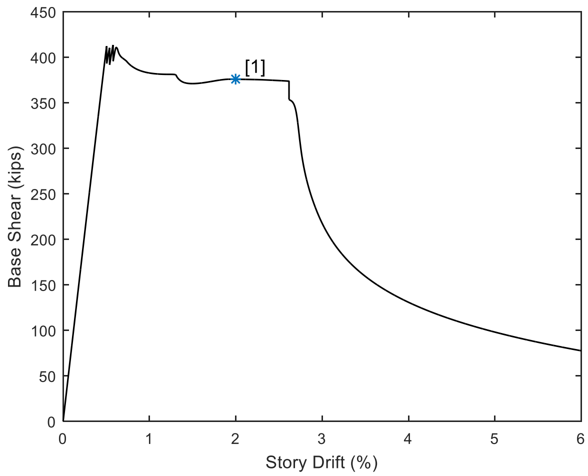


Figure 7. Response of OCBF16-5X-U (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Brace response (positive indicates compression and axial shortening).

7.2 Results for OCBF-4X-NU



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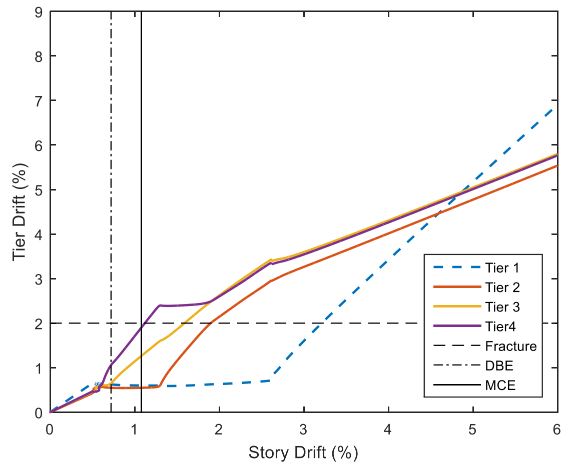
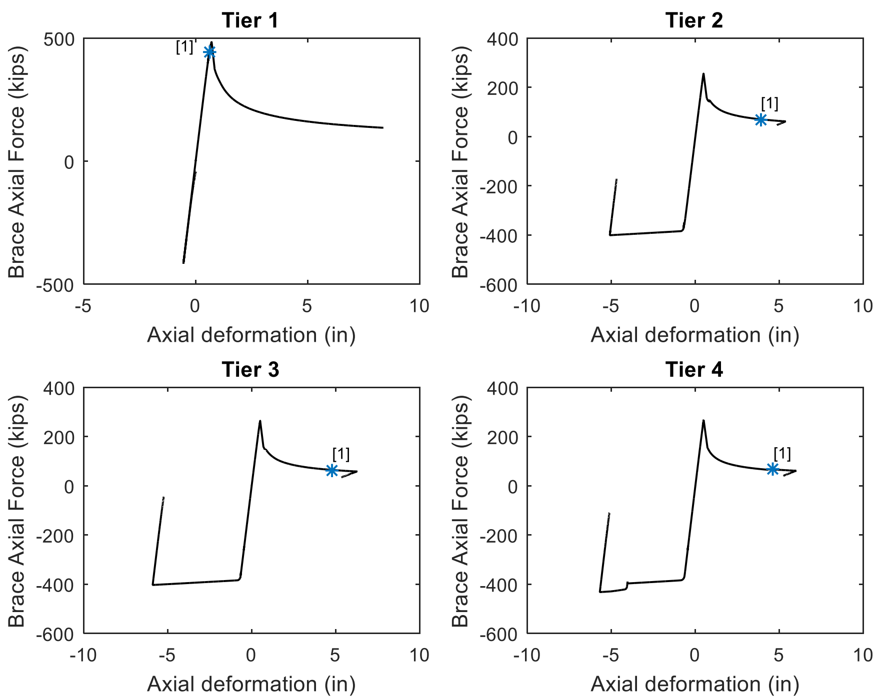


(b)



(c)

Figure 8. Response of OCBF10-4X-NU (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Brace response (positive indicates compression and axial shortening).

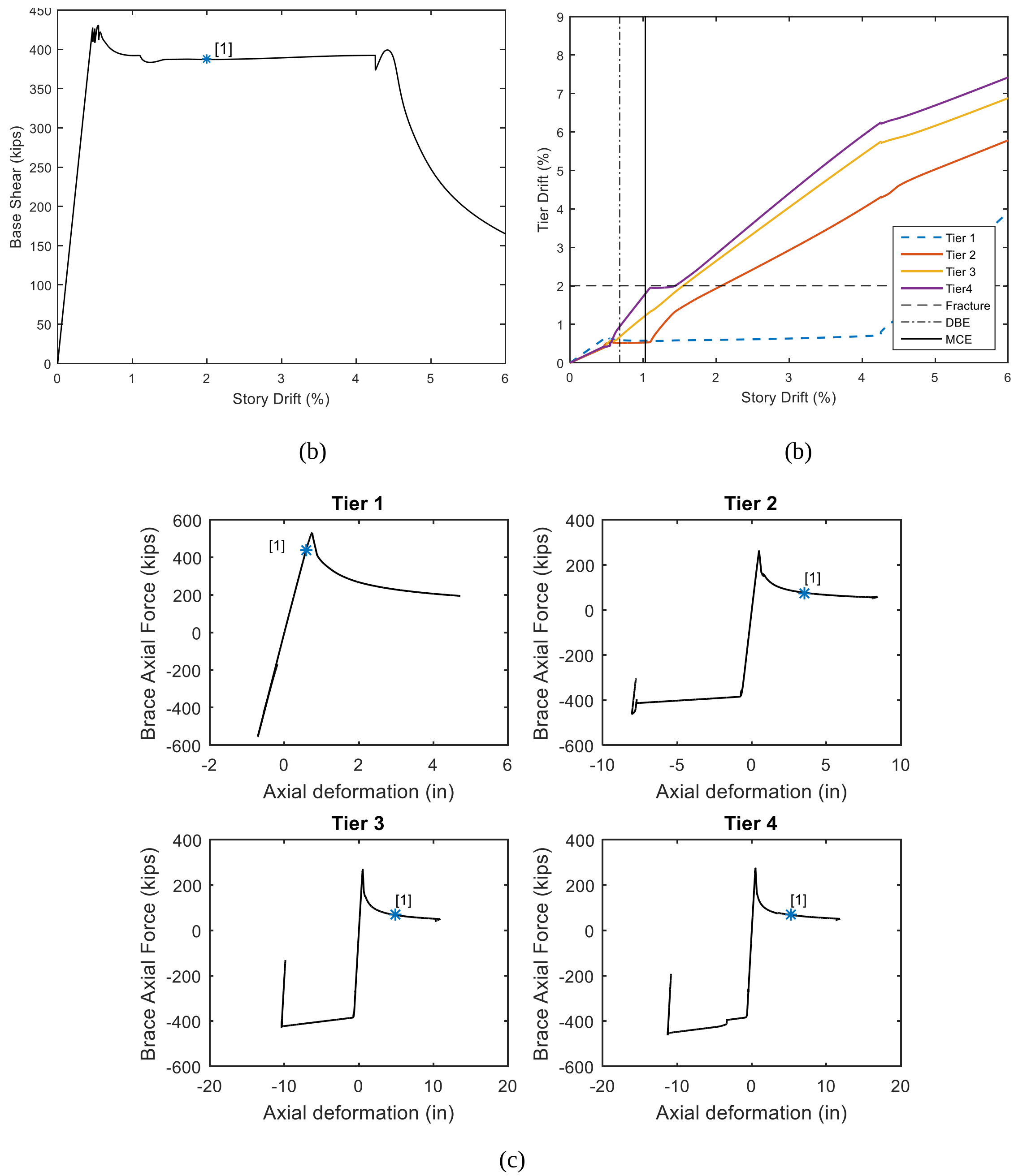


Figure 9. Response of OCBF16-4X-NU (a) Base shear vs. story drift (pushover curve); (b) Tier drift vs. story drift; (c) Brace response (positive indicates compression and axial shortening).