COMPARISON OF THE SEISMIC PERFORMANCE OF MULTI-STORY AND MULTI-TIERED BRACED FRAMES

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ABSTRACT

Steel braced frames are commonly used as lateral force resisting systems in seismic applications. In the case of all single-story steel buildings, it is more economical to use multi-tiered braced frames (MT-BFs) in which the braced bay is divided into multiple panels over the height. In contrast to multi-story frames (MS-BFs), MT-BFs lack intermediate out-of-plane supports or diaphragms between the base and the roof. While the primary energy dissipation mechanism in both systems is brace inelastic axial response, the unique conditions in MT-BFs have been shown to cause inelastic drift concentration in one tier that can lead to column instability from combined axial and flexural demands. This study uses nonlinear static analysis to quantify the differences in seismic demand and behavior of the two configurations. The results for the 2-tier/story frames clearly demonstrate the need to consider flexural demands in MT-BF column design. Further, while column buckling occurs at lower roof drifts for the MT-BFs, the difference is more pronounced for the 2-tier/story frames than the 3-tier/story frames that have essentially the same response. In general, the results confirm that the overall demand in columns is higher in MT-BFs, but column instability can still occur in MS-BFs.

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ABSTRACT

Steel braced frames are commonly used as lateral force resisting systems in seismic applications. In the case of tall single-story steel buildings, it is more economical to use multi-tiered braced frames (MT-BFs) in which the braced bay is divided into multiple panels over the height. In contrast to multi-story braced frames (MS-BFs), MT-BFs lack intermediate out-of-plane supports or diaphragms between the base and the roof. While the primary energy dissipation mechanism in both systems is brace inelastic axial response, the unique conditions in MT-BFs have been shown to cause inelastic drift concentration in one tier that can lead to column instability from combined axial and flexural demands. This study uses nonlinear static analysis to quantify the differences in seismic demand and behavior of the two configurations. The results for the 2-tier/story frames clearly demonstrate the need to consider flexural demands in MT-BF column design. Further, while column buckling occurs at lower roof drifts for the MT-BFs, the difference is more pronounced for the 2-tier/story frames than the 3-tier/story frames that have essentially the same response. In general, the results show that the overall demand in columns is higher in MT-BFs, but column instability can still occur in MS-BFs.

In the case of a tall single-story steel building, it is convenient and economical to use a multi-tiered configuration for the frame in which horizontal struts divide the braced-bay into multiple panels over the frame height. However, in contrast to multi-story braced frames (MS-BFs), the unbalanced forces at tier levels in multi-tiered braced frames (MT-BFs), due to post-buckling response of the braces, can only be resisted through column bending since mass is concentrated at the top of the tall story and inertial forces do not develop at the tier levels. Prior research [1, 2] has shown that during inelastic response, deformations tend to concentrate in one tier and impose additional

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flexural demands on the columns. In the case of braced frames, in-plane flexural demands are not directly considered in design, and the combined axial-flexural demands make the column susceptible to instability. In MT-BFs, column stability is further compromised due to the lack of intermediate out-of-pane supports or diaphragms between the base and the roof. The goal of the current research is to compare the seismic response of MS-BFs and MT-BFs and numerically study the demands imposed on the columns.

Prototype Frames and Numerical Model

The prototype frames for this study are used in a 40-ft-tall building, located in coastal California, with plan dimensions of 460 ft x 180 ft, and roof dead load and exterior wall weight of 25 psf each. The building is assigned to Site Class D, and Risk Category II with an importance factor of 1. The design spectral accelerations, $S_{D1}$ and $S_{DS}$, are 0.6g and 1.0g, respectively. All frames are designed as ordinary concentrically-braced frames with X bracing, using the equivalent lateral force procedure (including 10% amplification for accidental torsion) [3]. Member design is per AISC 360-10 [4] and AISC 341-10 [5], with ASTM A1085 HSS sections for the braces, and ASTM A992 W sections for both the columns and beams/struts. Columns are continuous over the frame height and oriented for weak-axis bending in-plane. Beams/struts are oriented for strong- and weak-axis bending in-plane for MS-BFs and MT-BFs, respectively.

For MT-BFs, the total seismic mass, $m$ (2710 kips) is concentrated at the roof level. With two braced bays in each direction, the design base shear is 230 kips. MS-BFs are designed to resist the same static base shear with a seismic mass, $m$, assigned to each additional story. Thus, where MS-BFs are used, the seismic weight and the number of frames in each orthogonal direction increase, and gravity loads are included at the story levels (these gravity loads are smaller due to interior columns). In this study, 2- and 3-tier/story configurations are used. The resulting design lateral load profiles and member sizes are shown in Figs 1(a), 1(b), 1(c) and 1(d).

A three-dimensional, fiber-based numerical model was created in the OpenSees [6] simulation platform, shown schematically in Fig 1(e). Columns and braces are modeled to capture flexural buckling response [1, 2]. A nominal yield strength of 50 ksi is specified for the columns, while an expected yield strength of 62.5 ksi is specified for the braces. For MT-BFs, the expected brace strength is reduced by 5% [1, 2]. The gusset plates are modeled using zero-length, non-linear rotational springs in conjunction with stiff connection end zones [7]. Elastic elements are used for the leaning column (P-Δ effect), beams, and struts. Point masses and tributary gravity loads are applied to the columns at the story levels as appropriate.

![Figure 1. Frame geometry and section sizes and schematic of numerical model.](image-url)
Nonlinear Static Analysis

Results of the nonlinear static (pushover) analyses are shown in Figs 2(a) and 2(b) for the 2- and 3-tier/story frames, respectively. The first row shows the overall base shear vs roof drift plots. The 2-tier/story frames exhibit similar response in the initial linear elastic region until brace buckling is initiated in the first tier/story, with successive brace buckling initiated in the upper tiers/stories. Differences in the response become pronounced after the peak lateral resistance is achieved when tension yielding occurs in the first-tier/story brace. The braces degrade in the post-buckling range, and the lateral resistance of the frames reduce. This behavior is typical of MT-BFs and at this point, combined axial and flexural demands on the column initiate column buckling and prevent tension yielding in the upper tiers. However, for the 2-story frame larger inelastic deformations occur in the first-story brace, and column buckling occurs at more than two times the roof drift. Other limit states (such as brace fracture in tension which is not modeled) may control in the 2-story frame prior to column buckling. The columns are further investigated by plotting the normalized (by the corresponding plastic section capacity) axial force \((p)\), in-plane moment \((m_x)\), and out-of-plane moment \((m_z)\) demands at the mid-height of the bottom tier/story. The maximum value of \(p\) occurs after brace buckling and tension yielding, but is lower in the 2-story frame than in the 2-tier frame. The maximum \(m_x\) value coincides with column buckling, but continues to increase in the 2-tier frame. The maximum value of \(m_x\) is also higher for the MT-BF. Here, the flexural demands in the MT-BF columns are noticeably higher, but column buckling occurs for both configurations. The higher demands arise since the column must carry the difference in shear capacity between the adjacent tiers, and the need to consider flexural demands in the 2-tier frame column design is evident.

In the case of the 3-tier/story frames, Fig 2(b) shows nominal differences in the pushover response, with column buckling around similar roof drifts for both configurations. Despite the smaller section, demands are only slightly lower in the 3-story frame columns. Further, the first-story brace shows significant inelastic response which may be indicative of the potential for brace fracture before column buckling. Thus, for this case, the behavior of multi-tiered and multi-story frames is very similar and the importance of flexural demands in column design as a unique consideration for multi-tiered frames is not as clear as in the 2-tier/story frames.

Conclusions

The seismic performance of multi-tiered and multi-story X-braced frames was evaluated in this study. MT-BFs, unlike MS-BFs, lack out-of-plane supports at the tier levels, which along with additional flexural demands during inelastic response can lead to column buckling. For this study, prototype frames with 2- and 3-tiers/stories were designed in accordance with the applicable seismic design provisions, and their response was assessed using nonlinear static (pushover) analysis. Initial linear elastic response, followed by brace buckling and tension yielding, and eventual column buckling occurs in all cases. However, differences in the response of MT-BFs and MS-BFs are particularly evident in the 2-tier/story case, and the need to consider flexural demands in MT-BF column design is clear. The same is not true for the 3-tier/story frames that exhibit very similar nonlinear response, indicating that flexural demands play a similar role in both cases and lead to column instability in both multi-story and multi-tiered frames.
Figure 2. Pushover analysis results.

References


