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# Seismic demand on columns in special concentrically braced frames

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ABSTRACT

A study on the seismic demand on the columns in special concentrically braced frames is presented to address two concerns. First, whether or not the columns remain elastic during an earthquake ground motion is investigated. In addition, sufficiency of using the first mode deformation, anticipated by the current design code, as the only possible deformation pattern for designing braced frames is studied. A set of twenty ground motions was applied to three 9-story buildings using two-story X-bracing and chevron bracing configurations. Two different braced-intersected girders were used in two-story X-braced frames to investigate the effect of beam strength on the frame response. Seismic responses of the frames were discussed in terms of seismic demand on the columns and braces. The study concludes that columns in two-story X-braced frames, designed based on current design code, experience yielding during an earthquake ground motion, and it is not safe to use the first mode deformation as the only possible deformation pattern for designing the braced frames. This study also finds that seismic demand on the braces in the two-story X-braced frames are quite significant and are prone to fracture.

## 1. Introduction

Special concentrically braced frames (SCBFs) have been among the most interesting lateral load resisting systems to the researchers after disappointing performance of special moment resisting frames (SMRFs) in the 1994 Northridge earthquake. SCBFs are lateral load resisting systems that dissipate earthquake energy through buckling of the compressive braces and yielding of the tensile braces. V-type, inverted V-type (chevron) and two-story X-bracing, consists of a V-type and an inverted V-type bracing in alternating stories, are three major categories of the bracing configurations in SCBFs. In the past two decades, extensive studies have been performed on the seismic behavior of the braces [1–9], gusset plates [10–12] and beams [13,14], but investigations about the columns as the most important members of a structure are scattered and scarce.

According to the AISC 341-10 section F2.3. [15], braces should be designed as a “column” member to resist the equivalent seismic forces calculated based on the ASCE7-10 [16]. Consequently, columns should be designed based on the expected capacity of the braces to ensure they remain elastic during an earthquake. For this purpose, three different analyses cases are proposed to be used for column design [15]. In the first two cases, all the tensile braces should be replaced by their expected tension capacity and all the compressive braces should be replaced by: (1) their expected buckling capacity; (2) their expected post-buckling capacity. In the third analysis case, compressive braces should be removed from the frame and lateral forces should be multiplied by the over-strength factor. The standard also states that braced frames must be designed for the first mode loading pattern and all tension and compression braces would reach their capacity simultaneously. In addition, designers are permitted to neglect the bending moment in the columns and they should be designed under a compression force derived from three abovementioned structural analysis cases. Whereas, studies have demonstrated that flexural demand in columns caused by non-uniform story drifts [17,18] would have a substantial effect on frame behavior and it is not safe for it to be neglected. As an attempt to solve this issue, MacRae et al. [19] proposed an empirical formula to take into account the effect of the story drift ratio (SDR) on the bending moment demand of the columns. SDR can be calculated by dividing the story drift by the story height. Moreover, experimental studies on the seismic demand on the steel columns demonstrate that columns experience yielding under various axial load ratios which is mainly due to the large flexural demand on the columns [20]. Limited studies have investigated the seismic performance of columns in ductile CBFs [21–25], and have proposed different methods to deal with columns in SCBFs. However, it is still unclear whether the first-mode deformation, used in the current design code, is the most critical pattern and what the effect of higher mode deformation is on seismic demand of columns.

In the present study, a typical nine-story braced frame was designed based on the current design codes [15,16] using two different bracing configurations, two-story X-bracing and chevron bracing. In the former configuration, two different design approaches were used: (1) considering both V-type and inverted V-type braces in the design

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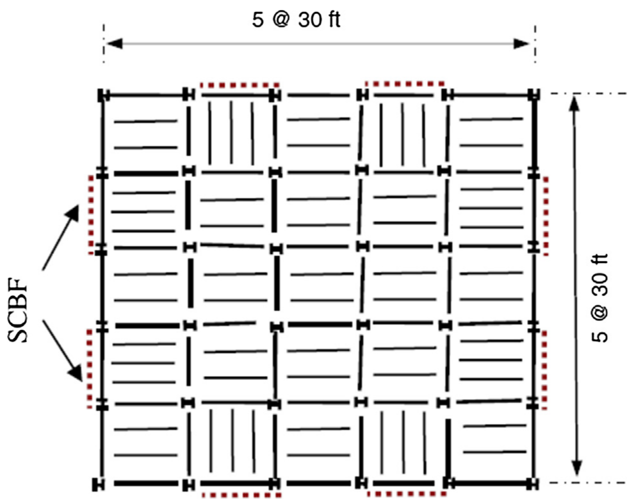


**Fig. 1.** Typical floor plan with locations of SCBFs.

procedure, resulting in a weak braced-intersected beam; (2) considering only inverted V-type braces, resulting in a strong braced-intersected beam. An ensemble of twenty ground motions was applied to these three braced frame and the results are presented in terms of seismic response on the columns and braces. In addition, effect of various deformation modes on the behavior of a two-story X-braced frame (TSXBF) was investigated in a general-purpose finite-element software [26].

## 2. Structures and earthquake ground motions

### 2.1. Building description

In the present study, three different braced frames were designed and their seismic behavior were investigated under various ground motions. Typical floor plan shown in Fig. 1 presents the orientation of the secondary beams and bay widths in each direction. It can also be seen that the SCBFs are located in the perimeter frames to resist lateral forces. The two different types of bracing configurations used in this study are presented in Fig. 2. Perimeter frames are assumed to carry a small portion of gravity loads based on their tributary area and half the lateral force in each direction is transferred to every SCBF as well. Interior beams and columns are designed based on the gravity load applied in their tributary areas.

Assumed dead and live loads of 80 psf and 50 psf, respectively, are applied on 3-1/2 in. thick concrete constructed on a metal deck with steel shear studs welded to the beams on each floor. The roofing system provides a non-flexible diaphragm that transfers lateral forces to the SCBF. The building is designed in conformance with the provisions of ASCE7-10 [16] for required design strength and AISC 341-10 [15] for seismic design requirements, and the building is assumed to be located on a site with $S_s$ and $S_1$ equal to 2.0 and 1.0, respectively. As the base shear, 22% of the building weight is applied to the building in each direction, and each braced bay is designed based on a quarter of the total base shear. The loading combination governing design of the braces is $(1.2 + 0.2S_{DS})DL + 1.0LL + \rho Q_E$, where $\rho$ (the redundancy factor) is assumed to be 1.3. Identical brace sizes are used for every two consecutive stories and brace sections are selected by considering the strength, slenderness ratio, and ductility criteria specified in AISC 341-10 [15]. Moreover, Beams and columns are designed based on the capacity of the braces according to the provisions of AISC 341-10 [15] with highly ductile and moderately ductile sections selected for columns and beams, respectively, to satisfy the current design code requirement. Round or rectangular HSS sections are chosen for braces, while W sections are used for beams and columns. In addition, gravity beams and columns are designed based on the load acting on their tributary area.

Previous studies have shown that current design codes have not been able to predict the proper required beam size in TSXBFs [13], mainly because the unbalanced force from the braces applied to the braced-intersected beam would be zero if the same section was used for braces in alternating stories. In other words, the beams are not designed for seismic loads which is not conservative. To overcome this issue, an additional frame has been designed by removing the V-type braces in the upper story of the brace intersected beams, leading to a strong beam similar to those usually used in chevron frames. The two different design approaches for TSXBFs are presented in Fig. 3. In this figure, $T_{ET}$ and $C_{EC}$ represent the expected yielding capacity and expected buckling capacity of the braces, respectively. For simplicity in comparing the results, the TSXBF with strong braced-intersected beams is referred to simply as “Frame S” and the regular TSXBF that is designed according to the current design code [15,16] is designated as “Frame W”, and the chevron frame is designated as “Frame C”. Table 1 shows the summary of the section sizes used for each member.

### 2.2. Earthquake ground motions

Ten pairs of earthquake ground motions compatible with site class D have been used in this investigation. Ground motions are selected from the PEER ground motion data base [27] using $S_{DS} = 1.333(g)$, $S_{D1} = 1.000(g)$, and $T_L = 12.0$ s. Response spectra of the ground motions are represented in Fig. 4 as black solid lines, and not more than two of the ground motions are taken from any one earthquake to avoid event bias. The target design spectrum achieved from ASCE7-10 [16] is also represented in this figure by a blue line. The period of the first

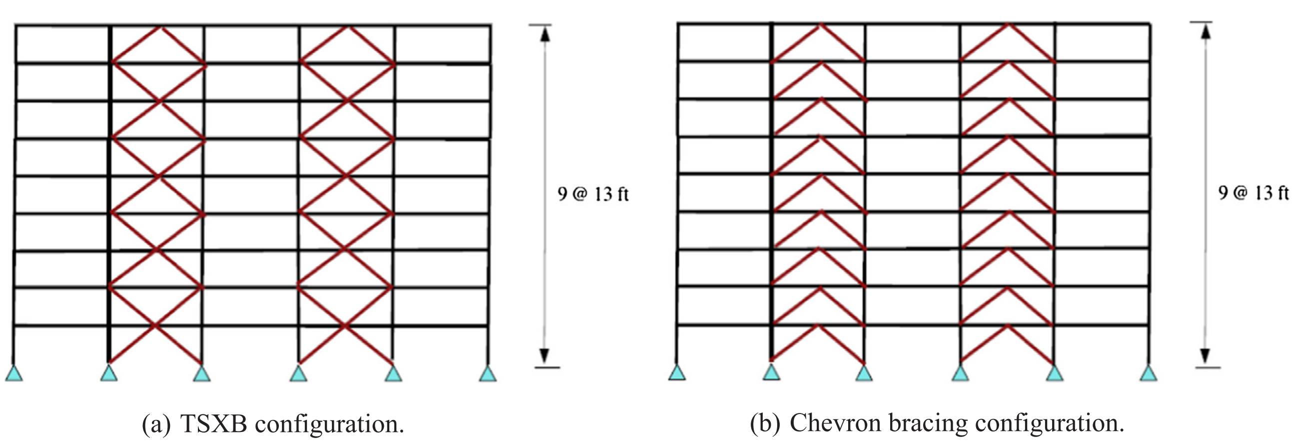


**Fig. 2.** Elevation of designed frames.