Engineering Structures 169 (2018) 68–80

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Enhancing seismic performance of tension-only concentrically braced beam-through frames through implementation of rocking cores

Shuling Hu[a,b], Wei Wang[a,b], Bing Qu[c,*]

[a] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[b] Dept. of Structural Engineering, Tongji University, Shanghai 200092, China
[c] Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, USA

ARTICLE INFO

Keywords:
Concentrically braced frame
Tension-only brace
Soft story
Rocking core

ABSTRACT

Beam-through concentrically braced frames consisting of tension-only braces (denoted as BTFs) have been progressively used as lateral force resisting systems in low-rise and mid-rise buildings in regions with seismicity. However, recent experimental and analytical investigations showed that the code-compliant BTF system may be vulnerable to the failure caused by the excessive inter-story drift ratio at a certain story (which is defined as the ratio of the inter-story drift to the height of the story) due to formation of the soft-story mechanism. This paper investigates the adequacy of the rocking core technology for mitigating such failures in the code-compliant BTFs. First, this paper discusses how the rocking core technology can be implemented in BTFs. Then, this paper presents a method to identify the soft story in a given BTF. Next, through parametric Nonlinear Response History Analyses (NRHA) of four representative benchmark BTF buildings, this paper investigates the validity of the rocking core technology in enhancing seismic performance of BTFs. Specifically, the influences of rocking core stiffness on the maximum inter-story drift ratio response and uniformity of the inter-story drift ratio distribution in each of the benchmark BTF buildings are quantitatively addressed based on the result database gleaned from the NRHA. Moreover, this paper establishes a seismic performance measure which considers both the maximum inter-story drift ratio response and uniformity of the inter-story drift ratio distribution. The seismic performance measure was used to interpret how the rocking core technology improves seismic performances of the demonstration buildings. Results from this research demonstrate that the rocking core technology can reduce the maximum inter-story drift ratio response while improving uniformity of the inter-story drift ratio distribution in BTFs. Also presented in the paper are some design recommendations for the rocking cores implemented in the BTFs based on the NRHA results.

1. Introduction

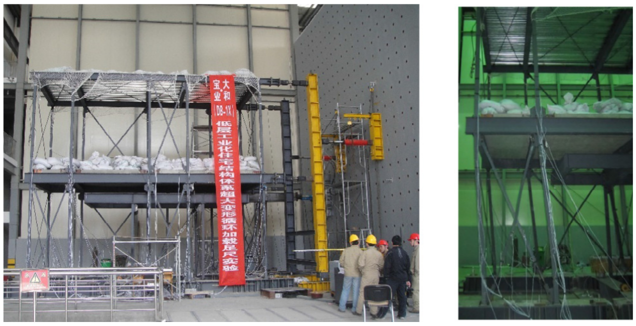
Steel concentrically braced frames (CBFs) are recognized as one of the most popular lateral force resisting systems in the building design community [1–6]. Compared with steel Moment Resisting Frames (MRFs), steel CBFs are more efficient in reducing inter-story drift responses caused by seismic forces. During earthquake events, the braces in steel CBFs are anticipated to yield and buckle under tension and compression, respectively. When a brace buckles, plastic hinges will form in the brace. As a result, inelastic strains usually concentrate over the brace plastic hinge regions, unavoidably causing ruptures in the brace due to the cumulative low-cycle fatigue damage.

To reduce the potential of brace rupture failures, steel plate braces have been proposed [7]. Due to their thin profiles, steel plate braces develop much lower degrees of inelastic strain concentrations compared with the other structural shapes (e.g., hollow structural shapes or wide flange members) under the same brace plastic hinge rotation. Compared with the other types of braces having different cross-section profiles but the same cross-section area, steel plate braces are much slenderer and thus have negligible compressive resistances (essentially exhibiting the tension-only behavior). Owing to their advantage in alleviating inelastic strain concentrations over the brace plastic hinge regions, the tension-only steel plate braces continued to find applications in low-rise and mid-rise steel CBFs in North America and Japan [8].

More recently, the beam-through CBFs consisting of tension-only braces (denoted as BTFs), in which the beams are continuous but the columns are discontinuous, were proposed [9–11]. Past experimental and analytical investigations demonstrated that BTFs can accelerate the construction process and help avoid severe damages in floors during

* Corresponding author.
E-mail address: bqu@calpoly.edu (B. Qu).

https://doi.org/10.1016/j.engstruct.2018.05.035
Received 24 January 2018; Received in revised form 22 April 2018; Accepted 11 May 2018
Available online 26 May 2018
0141-0296/



(a) the full-scale specimen prior to tests (b) the soft-story failure

Fig. 1. Performance of a full-scale BTF specimen previously tested.

earthquakes [10,12]. However, some past investigations completed to date also revealed that a BTF can be prone to the failure caused by the excessive inter-story drift ratio at a certain story (which is defined as the ratio of the inter-story drift to the height of the story) due to formation of the soft-story mechanism (referred to herein as *the soft-story failure*) [9]. Fig. 1 illustrates the soft-story failure observed in a full-scale two-story BTF specimen recently tested by this research team. Note that more information about the specimen and the test results are presented elsewhere [9]. Essentially, adopting discontinuous columns and tension-only braces can trigger the formation of a soft-story failure. Conceptually, the discontinuous columns reduce the vertical continuity and inherent capacity of the system to avoid inter-story drift ratio concentrations [13,14]. In addition, the tension-only braces have more pinched hysteretic behavior and reduced hysteretic energy dissipation capacity compared with the conventional stocky braces with non-negligible compressive resistance [15]. Further, the Chinese Code for Seismic Design of Buildings (GB50011-2010) [16] has no control of overstrength uniformity along the height of a building. As will be addressed in detail in Section 4 of this paper, overstrength uniformity affects yielding sequence and distribution of the yield members in the system. The vulnerability of BTFs to a soft-story failure overshadows the other recognized advantages of the system (such as the better tolerance to brace rupture failures, the ease of construction and the reduced floor damages), preventing the widespread acceptance of the system in the building design industry. Therefore, a pressing research need exists to enhance seismic performance of BTFs (particularly, the existing BTF constructions).

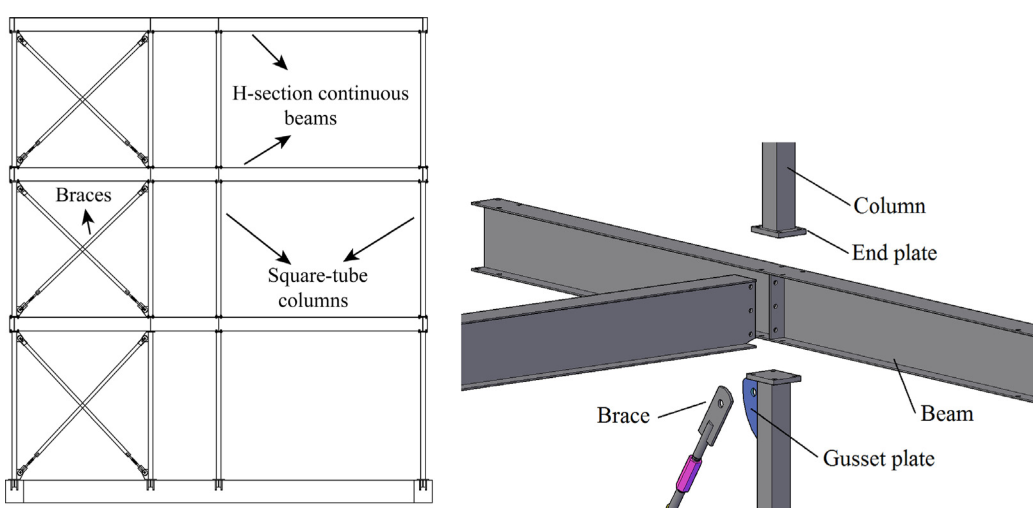
To mitigate the soft-story failure, the rocking core technology was recently developed for steel building frames [3]. Although past analytical and experimental investigations have demonstrated that the rocking core technology is effective in avoiding the soft-story failure in conventional steel CBFs and steel MRFs [1,3–6,17], it is unclear whether the rocking core technology would remain valid in improving seismic performance of BTFs (which have discontinuous columns, extremely pinched hysteretic behaviors, and reduced hysteretic energy absorption capacities).

The main objective of this research was to evaluate the adequacy of the rocking core technology for seismic performance enhancement in BTFs and develop recommendations for designing the rocking cores in BTFs if applicable. To achieve the objective, this paper first discusses how the rocking core technology can be implemented in BTFs. Then, this paper presents a method to identify the soft story in a given BTF. Next, through parametric Nonlinear Response History Analyses (NRHA) of four representative benchmark BTF buildings, this paper investigates the validity of the rocking core technology in enhancing seismic performance of BTFs. Specifically, the influences of rocking core stiffness on the maximum inter-story drift ratio response and uniformity of the inter-story drift ratio distribution in each of the benchmark BTF buildings are quantitatively addressed based on the result database gleaned from the NRHA. Moreover, this paper establishes a new seismic performance measure which considers both the maximum inter-story drift ratio response and uniformity of the inter-story drift ratio distribution. The seismic performance measure was further used to interpret how the rocking core technology improves seismic performances of the demonstration buildings. Based on the results from the NRHA, design recommendations are given to design the rocking cores for the BTFs. The following presents in detail the related work.

2. Implementation of the rocking core technology in BTFs

Fig. 2(a) presents an elevation view of a typical BTF. As shown, the frame consists of square-tube columns, continuous beams and slender steel plate braces with the negligible compressive resistance. As shown in Fig. 2(b), each column is connected to the continuous beam through the end plates fastened by high-strength bolts; the braces are connected to the columns through the gusset plates and high-strength bolts. Note that the column-to-beam connections have negligible moment resistances according to past investigations [12].

Fig. 3 illustrates an implementation plan of the rocking core



(a) elevation (b) brace-to-column and column-to-beam connections

Fig. 2. Description of a conventional BTF.