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Full-scale shake table tests of the tension-only concentrically braced steel beam-through frame

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ABSTRACT

The tension-only concentrically braced steel beam-through frame (TCBBF) has the potential to enhance the seismic and post-earthquake performance for low-rise buildings in low to moderate seismic regions. To a better understanding of the dynamic response of TCBBFs, full-scale shake table tests under different seismic hazard levels and aftershocks were conducted on a three-story structural model. From the test results, the damage-control and low-residual-displacement behaviors were verified firstly. Under maximum considered earthquake (MCE), the main frame nearly remained elastic while all the braces yielded and there was almost no residual displacement. Under stronger earthquakes exceeding the MCE, yielding occurred at the beam-column connections, and the main frame demonstrated pinching behavior. Meanwhile, the residual displacement of the structure was still at a very low level. The tension-only braces played a key role in the seismic behavior. The existence of prestress made the braces able to sustain a little compression and thus increased the initial lateral stiffness of the structure. The slackness of the brace would enlarge story drift response and also induce dynamic impact due to the sudden tensioning. This impact effect was effectively controlled because of the high ductility of the braces. Tightening the slack braces was a convenient way to restore the structural behavior if the main frame was not damaged.

1. Introduction

Ductility of a structure ensures better structural performance against collapse, but normally at the cost of severe damage and permanent residual displacement to the structure after a strong earthquake. These structures may remain standing during the earthquake but need to be demolished if the repair cost is too high. Many columns in bridges were demolished and new columns were built due to the large residual drifts after the 1995 Kobe earthquake [1]. About 900 buildings and 10,000 residential homes had to be demolished after the 2011 Christchurch earthquake [2]. Therefore, more stringent seismic performance objectives need to be achieved to ensure better post-earthquake performance.

One design approach is to introduce damage-control strategy, i.e., restricting the damage to a specific set of structural elements that can be readily repaired [3]. After earthquakes, only the damaged structural elements need to be repaired. This would simplify the repair process, reduce the downtime of structure and lower repair cost. The structural damage could be concentrated in different kinds of structural elements which yield prior to the other part of the structure. These elements could be structural members [4, 5] or energy dissipation devices [6, 7]. These structural elements are characterized by stable hysteretic behavior and expected to dissipate energy effectively during earthquakes.

Another aim is to reduce the residual displacement of the structure after earthquakes. Since residual displacement has been identified as a key factor in determining the technical and economic feasibility of repairing damaged structures [8]. Permissible residual displacement levels have been studied and the most accepted criteria is that it will be less expensive to repair a building structure than to rebuild it if the residual drift is smaller than 0.5% [9]. The residual displacement performance is strongly affected by the features of hysteretic behavior. Structures with larger post-yield stiffness or loading and unloading stiffness degradation generally have smaller residual displacement [10, 11]. More recently, structural systems with self-centering hysteretic behavior were developed to reduce or eliminate residual displacement after earthquakes. The hysteretic behavior of self-centering structures is characterized as flag-shaped, which can be contributed by post-tensioning tendons, rocking mechanisms or the shape memory alloy (SMA) [12–14].

Concentrically braced frames (CBFs) have favored by designers because of their economic advantages particularly in the cases where the design was governed by the drift requirement. A detailed evaluation on the seismic design and behavior of CBFs can be found in this

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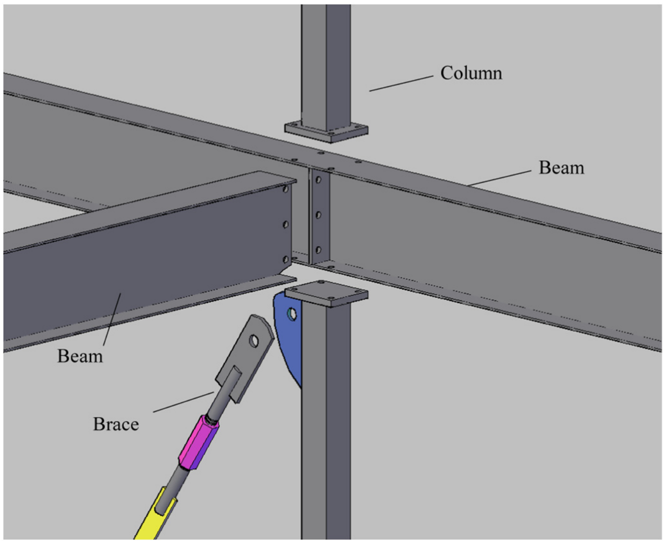

Fig. 1. Illustration of TCBBFs system.

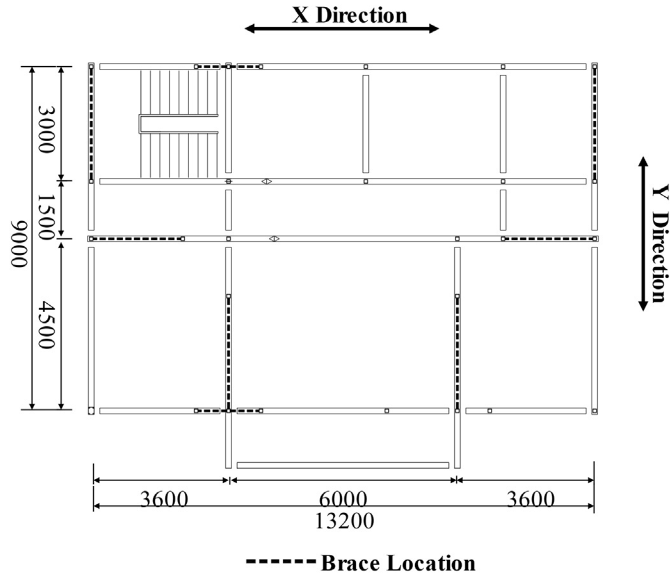

Fig. 3. A typical plan of TCBBF in engineering application (mm).

literature [15]. Recently, seismic performance of CBFs for low to moderate seismic regions is gaining attention [16]. In China, the most commonly used design basic ground motion acceleration is 0.1 g and it is not larger than 0.2 g in majority part [17]. Though characterized as deteriorating pinched hysteretic behavior and prohibited from medium- and high-rise buildings in active seismic areas, the tension-only concentrically braced frames (TOCBFs) continues to be used extensively for low-rise industrial, commercial and residential steel buildings in moderate seismic regions [18]. This paper focus on an innovative TOCBFs, termed as tension-only concentrically braced beam-through frames (TCBBFs) [19] to provide enhanced seismic performance. It is one type of damage-control and low-residual-displacement structural systems and mainly used for low-rise prefabricated buildings in low to moderate seismic regions.

This structural system is composed of a strong-beam-weak-column frame (main frame) and slender braces as shown in Fig. 1. All the structural components can be easily manufactured which makes the structural system economical. All the connections are bolted, which also aids rapid construction. The structural behavior prior to the yielding of the main frame is shown in Fig. 2. In the figure, k,V and Δ represent stiffness, yield force, and yield displacement, respectively, while the subscripts b and f stand for the braces and the main frame. The main frame can remain elastic under large deformation as the columns are relatively slender. The tension-only braces would yield much earlier than the main frame and would dissipate a certain amount of energy. As the braces buckle under very small compression, the main frame would re-center to the original position after earthquakes without damage. In this way, the braces can be easily replaced as they are connected to the main frame by bolts. The TCBBFs have been previously tested as prototype of a two-story frames under static loading [19]. The results show that the damage is concentrated on the braces and there is nearly no residual displacement when the story drift ratio is up to 2%.

However, some weakness should be paid attention to when applying this structural system. CBFs are prone to exhibit soft-story mechanism and this tendency is stronger when the braces are tension-only. The tension-only braces will be elongated and become slack after yielding and this phenomenon may bring other detrimental effects. These effects include progressively increasing of story drift, impact loading and

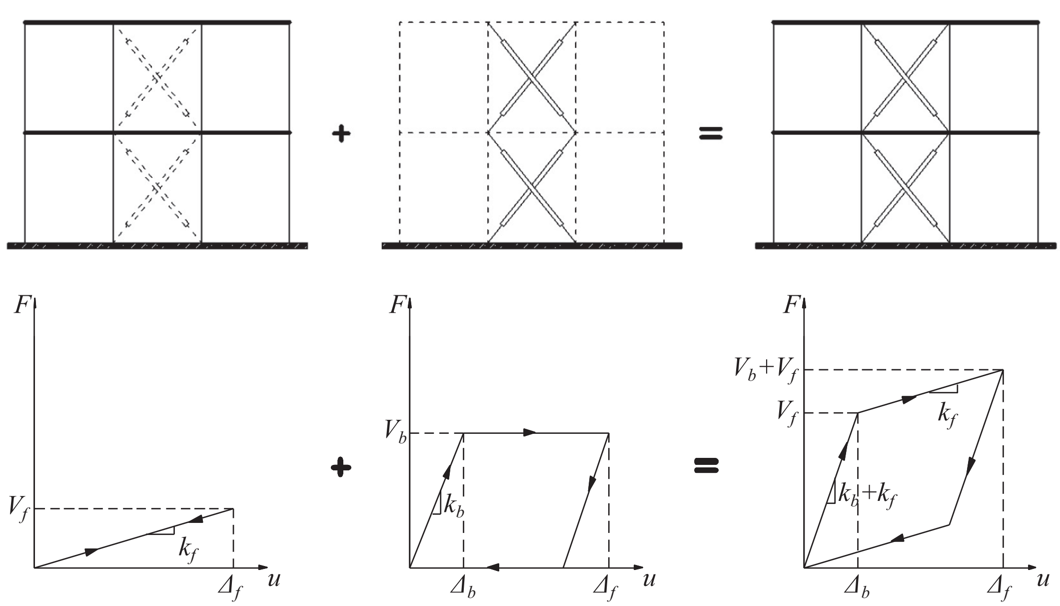

Fig. 2. Structural behavior of TCBBFs prior to the yielding of the main frame.