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Resilient steel frames installed with self-centering dual-steel buckling-restrained brace

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ABSTRACT

As one type of effective earthquake-resisting structural systems, buckling-restrained braced frames are expected to provide good seismic performance through significant plastic yielding to dissipate earthquake energy. This plastic deformation can cause significant structural damage and residual drift, leading to high retrofitting cost or even demolishment of structures after strong earthquakes. As a result, development of new systems that can not only dissipate seismic energy, but also possess self-centering ability, becomes necessary. This paper makes use of a newly proposed type of self-centering dual-steel buckling-restrained braces (SC-DBRBs). The SC-DBRB consists of a low-yield-point steel and a high strength steel, in which the low-yield-point steel mainly provides energy dissipation ability, and the high strength steel offers self-centering ability and additional energy dissipation ability during strong earthquakes. Compared with a conventional BRB (CBRB) commonly with a typical bilinear constitutive model, the SC-DBRB has a trilinear hysteretic behavior, leading to early re-yielding of the low-yield-point steel during subsequent strain reversals. This early re-yielding mechanism can greatly mitigate residual deformation of the SC-DBRB. In this paper, the constitutive model of the SC-DBRB is first established, and its correlation with main design parameters is also discussed. To demonstrate the self-centering ability of the SC-DBRB and its effect on post-earthquake performance of structures, a series of six-story and nine-story steel frames were numerically investigated using ABAQUS: unbraced frames, CBRB-equipped frames and SC-DBRB-equipped frames. Time history analysis results show that the SC-DBRB can effectively reduce residual drift.

1. Introduction

1.1. Background

It is known that a buckling-restrained braced frame (BRBF) is a good seismic-resisting system since buckling-restrained braces (BRBs) [1] can provide excellent energy dissipation capacity. A number of studies [1–15] have demonstrated satisfactory seismic performance of BRBs and BRBFs, generally providing adequate life safety for design level earthquakes. However, a residual drift beyond 0.5% for conventional BRBFs along the building height triggered by large plastic deformation of BRBs is a critical issue that makes a building impossible or expensive to retrofit [16,17]. In addition, long downtime of the building leads to additional economic loss. Investigation on the 2011 Christchurch earthquake showed that >1200 buildings had to be demolished as a result of large residual drift although they were not destroyed completely, which caused huge economic loss of $4–$13 billion USD [18]. Therefore, development of novel self-centering earthquake-resilient structures [15,19–22] is of significant importance for researchers and engineers. This paper proposes a novel type of self-centering BRBs consisting of two types of steel with different yield points, which is a new robust and resilient structural component for implementation in braced frames. This self-centering dual-steel buckling-restrained brace (SC-DBRB) is demonstrated to have excellent self-centering property.

1.2. Relevant prior research

BRB is a robust structural member with stable hysteretic behavior and high energy dissipation capacity. A conventional BRB (CBRB) has the following main components: a steel core component that provides axial stiffness, load-carrying capacity and energy dissipation capacity; a restraining component that prevents the core component from large local or global buckling deformation under compression; and unbonding material between the aforementioned 2 components. The restraining component is commonly a concrete filled steel tube or an assembly of several steel plates, and the steel core component is made of steel with high ductility. Owing to favorable energy dissipation capacity of the BRBs, BRBFs have been widely employed in practice as a high performance seismic-resisting system recently [2,23,24]. However, they are

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still susceptible to large post-earthquake residual drift under a strong earthquake which is mainly due to the low secondary stiffness of CBRBs [1,2,17]. As a result, although BRBFs offer the above advantages over traditional steel structures, lacking of self-centering ability is still a significant shortcoming considering the high retrofitting costs or even demolishment of damaged structures.

Self-centering earthquake-resilient structures with both energy dissipation and self-centering abilities under strong earthquakes are promising solutions for design of structures in regions with high seismic risk. Self-centering systems can be divided into 5 categories: (1) systems equipped with post-tensioned (PT) steel components that develop flexural gap opening at specified connections when a load is applied [20,22,25–28]; (2) rocking systems that allow uplift at the base of a structure when an earthquake occurs [29–32]; (3) systems that improve the shape and distribution of inter-story drift ratios, stiffening top story and enforcing the lateral shape of the building from a cantilever-like to shear-type [33]; (4) dual systems that reduce the drift ratio and to restore the building, with a deformable moment-resisting frame (MRF) working in parallel with the eccentrically braced frames (EBF) with removable link [34]; (5) braced frame systems equipped with self-centering buckling-restrained braces (SC-BRBs) that reduce post-earthquake residual drift [35–39]. Compared with the first 4 classes of self-centering systems, SC-BRB can be easily constructed and connected to a frame. Therefore, SC-BRBs made of PT tendons [40], memory alloy [16,41–44], and other types of SC-BRBs [45] were developed which exhibited favorable self-centering capacity in the experimental and analytical investigations.

1.3. Research objective of this study

The objective of this study is to develop a high-performance seismic-resisting brace with a trilinear constitutive model, which can provide both energy dissipation and self-centering abilities. The main feature of the SC-DBRBs is parallel connection of steel core plates with different yield strength, leading to 2 yield points in the hysteretic curve. In this paper, theoretical derivation of the trilinear hysteretic behavior was conducted, which was validated by numerical analysis results using ABAQUS [46]. Key parameters affecting the trilinear hysteretic behavior were also investigated. To demonstrate effectiveness of the proposed SC-DBRB in controlling the residual drift of the structures, time history analyses on six-story and nine-story frames with/without BRBs implemented were carried out, the results of which showed that erection of the SC-DBRBs can greatly reduce both the maximum and post-earthquake residual story drifts of the frames.

2. Characteristics of SC-DBRB

2.1. Design concept and hysteretic properties

The configuration of an SC-DBRB assembly is illustrated in Fig. 1. The SC-DBRB in this study consists of the following main components:

1. A steel core component consists of a low-yield-point (LYP) steel plate and a high strength steel one. The steel core component dissipates seismic energy through cyclic plastic yielding. The LYP steel plate is mainly used as an energy dissipation element, and the high strength steel plate is taken as both a self-centering and energy dissipation element. The steel plates are connected in parallel to ensure that they have the same deformation under cyclic loading.
2. The restraining component is nominally unstressed and provides enough lateral buckling restraint for the steel core component. The restraining component has to have enough stiffness and strength to prevent global buckling of the whole SC-DBRB and also restrain the buckling deformation of the steel core component. Details to avoid buckling at the connection regions of the core component are also critical for the design of the SC-DBRBs. There is also a gap between the steel core plates and restraining components to avoid excessive contact force due to expansion and flexural deformation of the core plate under compression. The expansion of the core steel plates is mainly induced by the Poisson's effect.
3. Unbonding material is located between the steel core component and the restraining component to reduce frictional force between them under compression.

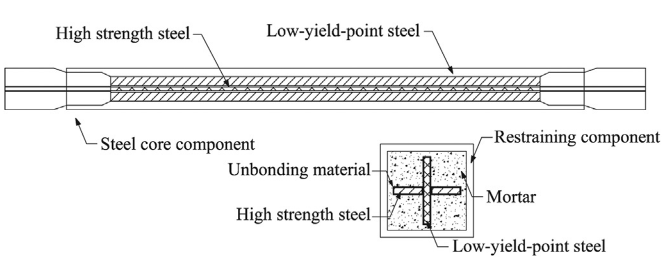

Fig. 1. SC-DBRB components.

Compared with conventional SC-BRBs with complicated details and additional PT tendons, the newly proposed SC-DBRB is attractive since no complicated manufacturing efforts are required and the proposal is much more economical.

The energy dissipation and self-centering mechanisms of the SC-DBRB are presented in Fig. 2. The SC-DBRB has 2 yield points for the difference in the elastic ranges between the LYP and high strength steels. The ideal average stress-average strain curve of the SC-DBRB is presented in Fig. 2, where the average strain is obtained by dividing the axial displacement by the length of the yielding portion, and the average stress is the ratio of the axial force to the original cross-sectional area of the core plates. Different from CBRB commonly with a single yield point, the SC-DBRB has 2 yield points under monotonic loading. The first yield point in Fig. 2 is mainly governed by yielding of the LYP steel when the high strength steel is still in the elastic stage. The second yield point in the figure is mainly controlled by yielding of the high strength steel.

Compared with the typical bilinear kinematic hardening behavior for a CBRB, a trilinear kinematic hardening model as illustrated in Fig. 3 can be employed for the SC-DBRB. In the figure, the 2 yield points are respectively denoted as Points A and B. The trilinear kinematic hardening model can be divided into 3 stages. At Stage OA, the SC-DBRB maintains the elastic state since both the LYP and high strength steels are within the elastic range. At Stage AB, the LYP steel core plate yields while the high strength steel still maintains the elastic state. Compared with a CBRB, the SC-DBRB exhibits a high secondary stiffness, which is beneficial to reduce the total plastic deformation of the SC-DBRB. At

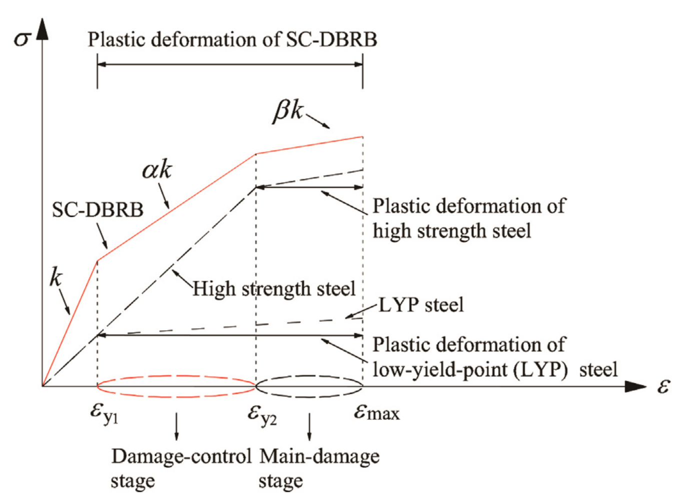

Fig. 2. Design concept of SC-DBRB.