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Influence of tube length tolerance on seismic responses of multi-storey buildings with dual-tube self-centering buckling-restrained braces

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ABSTRACT

The dual-tube self-centering buckling restrained brace (SC-BRB) is a novel bracing system with both self-centering and energy dissipation capabilities. However, the actual initial stiffness of SC-BRBs can be remarkably lower than theoretical values due to the length fabrication tolerances in bracing tubes, which may in turn influence the seismic performance of braced structures. Based on the working mechanism and hysteretic response of dual-tube SC-BRBs, this paper first analyses the influence mechanism of tube length tolerance on the initial stiffness of the self-centering system. The initial stiffness modification coefficient β is defined, and its calculation is established. Computational models are constructed for 4- and 12-storey steel frame buildings with dual-tube SC-BRBs. Nonlinear dynamic analysis is performed to investigate the influence of different values of β on the seismic response of the structures. The results show that the floor acceleration decreases significantly, except the top floor, with the reduction of β, which is introduced by tube length tolerance. However, the peak storey drift does not increase significantly, especially for 4-storey building. The residual storey drifts under different β are all very small, which indicates that the reduction of β has little influence on the self-centering capacity of the structures.

1. Introduction

In the design of traditional aseismic structural systems, e.g., moment resisting frames (MRFs) and concentric brace frames (CBFs), a high degree of plastic deformation is allowed to occur in structures in moderate or major earthquakes; in this manner, seismic energy is dissipated to control the seismic response of structures. The internal forces in structural components and base shear force can also be controlled [1]. While these design considerations can prevent the collapse of structures and assure the safety of occupants, they may also lead to damage and significant residual deformation in the structures, which increases the difficulty and cost of repair following earthquakes. In an investigation of structures in Japan following earthquakes, McCormick et al. [2] found that when the residual deformation exceeds 0.5%, the cost of repair exceeds that of rebuilding. Modern resilient structures [3] require that the structural system restore its function quickly after earthquakes with little or no maintenance. These structural systems slightly increase the initial building cost but significantly reduce the lifecycle cost related to earthquake damage [4]. To ensure the restorability of these structures, their degree of damage and residual deformation should be managed; the most effective method for managing residual deformation is for the structure to self-center, or automatically restore its initial position.

Presently, self-centering structural systems can be divided into three main types: (1) post-tensioned (PT) beam-column connections [5,6], (2) rocking systems [7,8], and (3) self-centering braces. Among these systems, the first two allow gap formation in beam-column or column-base connections, which may pose substantial challenges associated with connection to the gravity system and the transfer of inertial force [9]. Self-centering braces can be used in place of conventional braces without changing the construction details of the main frame. Recently, a self-centering energy-dissipative (SCED) brace was developed using friction devices and a dual-tube self-centering system with PT aramid-fibre tendons [10,11]. Cyclic loading tests showed that the brace has a stable energy dissipation capacity and self-centering characteristics. To lower the tendon elongation capacity requirement, Chou et al. [12,13] proposed a dual-core self-centering bracing system consisting of three steel bracing members, two PT element sets and friction devices. The deformation capacity of the brace is doubled through the serial connection of two sets of PT tendons. Some researchers have also introduced shape memory alloys (SMA) into self-centering braces both to create a self-centering force and to dissipate energy [14–16].

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Buckling restrained braces (BRB) [17–21] have been widely applied in practice due to their superior energy dissipation capacity and stable hysteretic characteristics. However, a low post-yield stiffness can lead to large residual deformation in structures after earthquakes [22,23]. To address this drawback, Miller et al. [24] introduced a self-centering system of SCED into BRBs to form triple-tube self-centering buckling restrained brace (SC-BRB) with SMA PT rods in which two tubes work as self-centering pushing struts and one more tube is used to restrain core plate buckling. Zhou et al. [25,26] developed a dual-tube SC-BRB system with basalt fibre-reinforced polymer (BFRP) tendons. The dual tubes work as both pushing struts and restraining tubes to simplify the brace construction and lower its weight. Moreover, BFRP tendons, which can be used as the pretensioned rods of a self-centering system, are substantially cheaper than SMA while possessing sufficient elongation capacity. Experimental results have shown that SC-BRBs exhibit a typical flag-shaped hysteretic response and that the self-centering system functions as expected.

During experiments on SC-BRBs, the actual initial stiffness of the specimen is substantially less than its theoretical value: this is primarily because the length tolerance between two bracing tubes leads to a reduction in the initial stiffness of the self-centering system. Erochko [27] and Chou et al. [12] observed a similar phenomenon during their experiments on SCEDs. They investigated the influence of tube length tolerance on the initial stiffness and hysteretic characteristics of the brace at the component level. Because the existing post-tensioned SC-BRBs [24–26] have adopted similar configuration of self-centering system as SCED, the tube length tolerance will also affect the initial stiffness of SC-BRBs. Nevertheless, different from the working mechanism of SCED, the initial stiffness of SC-BRBs results from the stiffness of the self-centering system and that of the core plates; consequently, the influence mechanism of tube length tolerance also differs. Moreover, few studies have addressed the influence of this initial stiffness reduction on the seismic performance of structures with self-centering braces [28].

In this paper, the equations for determining the initial stiffness modification coefficient β induced by tube length tolerances are developed for dual-tube SC-BRBs. The influence of β on the hysteretic performance of the braces is analysed. Two steel frame buildings (4-storey and 12-storey) are designed using SC-BRBs with three different values of β. Nonlinear dynamic analyses are performed for the six structural models under two groups of earthquake ground motions with different strength grades. The influence of β on the seismic response of these structures is investigated.

2. Concept of dual-tube SC-BRB

Fig. 1(a) shows the configuration of dual-tube SC-BRBs [25,26], which primarily consist of two systems: an energy dissipation system and a self-centering system. The energy dissipation system includes two parallel steel core plates, filling plates, an inner tube and an outer tube. The core plates are subjected to external load and dissipate energy by yielding in both tension and compression. Two ends of the core plates protrude from notches in the end plates to form the end connections of the brace, which connect to the main frame. The filling plates and inner and outer tubes are used to restrain the core plates to prevent their in-plane and out-of-plane buckling. The inner and outer tubes also work with the BFRP tendons and end plates to form the self-centering system. The right end of inner tube is welded to core plates and its left end is free, whereas the left end of outer tube is welded to core plates and its right end is free. BFRP tendons are tensioned and anchored to the end plates against the inner and outer tubes to create an initial compression in these two bracing tubes.

Fig. 1(b) shows the working mechanism of dual-tube SC-BRBs. When the brace is in tension, for the tensile deformation of core plates, the inner tube and outer tube will move in opposite directions to push against the end plates at their welding ends, which will result in gaps between the non-welded ends of the tubes and the end plates, leading to the elongation of the tendons. When the brace is in compression, bracing tubes move in opposite directions, pushing against the end plates on the non-welded ends to enable the compressive deformation of the core plates. Gaps are then generated between the welding ends of the tubes and end plates, leading to the elongation of the tendons. Therefore, whenever the brace is in tension or compression, both of the end plates move apart to stretch the tendons, providing a restoring force to overcome the plastic deformation of the core plates: in this manner, the self-centering mechanism can be achieved. The phenomenon in which both inner and outer tubes separate from the end plates at either side is defined as the activation of the self-centering system.

Fig. 2 shows the hysteretic responses of SC-BRBs, BRBs and self-centering (SC) systems. The stiffness of SC-BRBs (k) can be obtained by superposing the stiffness of BRB (k_{co}) and the self-centering system (k_{sc}), i.e.,

$$k = k_{co} + k_{sc} \tag{1}$$

In Fig. 2, u_{ys} is the activation displacement that denotes the axial deformation of the brace when the self-centering system is activated, F_{ys} is the activation load that denotes the axial force in the brace when its deformation reaches u_{ys}, and F_P is the pretension force applied in the BFRP tendons. The hysteretic curve of the self-centering system exhibits bilinear characteristics. When brace deformation is smaller than u_{ys}, both the inner and outer tubes only undergo axial deformation without relative motion under the pretension force. The stiffness of the self-centering system at this time is defined as the initial stiffness (k_{sc1}), which can be expressed as

$$k_{sc1} = k_{in} + k_{ou} + k_p \tag{2}$$

where k_{in}, k_{ou} and k_p are the axial stiffness of the inner tube, outer tube and tendons, respectively. When brace deformation is larger than u_{ys}, the self-centering system is activated. Both inner and outer tubes overcome F_P and move apart, resulting in tendon elongation. At this time, the stiffness of the self-centering system (k_{sc2}) is only the stiffness of the tendons (k_p). The hysteretic curve of BRB resembles a parallelogram, and its stiffness (k_{co}) oscillates between the elastic stiffness (k_{co0}) and plastic stiffness (k_{co1}) under cyclic tension and compression loads. Because of the action of the self-centering system, hysteresis in SC-BRB is characterised by a typical flag shape. Compared with the hysteretic responses of BRB, SC-BRB can effectively reduce and even eliminate the residual deformation of the brace. As shown in Fig. 2, when F_P is equal to or greater than the compressive yielding force of the core plate when considering strain hardening, the residual deformation of SC-BRB is smaller than u_{ys} to achieve ideal self-centering.

3. Influence of the tube length tolerance

3.1. Influence of tube length tolerance on the initial stiffness of the self-centering system (k_{sc1})

Under ideal conditions, the lengths of the inner and outer SC-BRB tubes should be equal; as such, the initial stiffness of self-centering system k_{sc1} is captured in Eq. (2). However due to fabrication tolerance, a length difference ΔL between the inner