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Performance of an innovative self-centering buckling restrained brace for mitigating seismic responses of bridge structures with double-column piers

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ABSTRACT

Buckling restrained braces (BRBs) are normally incorporated in the beam-column structures to serve as energy dissipation members due to their stable hysteretic behavior. However, the structures equipped with BRBs may suffer excessive residual deformations when they are subjected to large earthquakes. To minimize the residual deformations of the structures with traditional BRBs, a novel self-centering buckling restrained brace (SC-BRB) consisting of a self-centering system and a traditional BRB system is developed in the present study. Large-scale experimental studies are carried out and the hysteretic behavior of the proposed system is compared with the traditional BRB and self-centering brace (SCB). Experimental results show that the SC-BRB exhibits flag-shaped hysteresis response with a small residual deformation and a moderate energy dissipation capability. The proposed SC-BRB is applied to a reinforced concrete (RC) double-column bridge pier for seismic retrofitting. Nonlinear dynamic analyses are carried out to examine its effect on the seismic behavior of the bridge. Numerical results demonstrate that the bridge equipped with SC-BRB system shows much smaller residual displacement compared to the ones equipped with traditional BRB and SCB systems. Numerical results also indicate that SC-BRB system tends to amplify the peak acceleration of the bridge.

1. Introduction

The recent occurrences of highly devastating earthquakes in China, Chile, Japan and other countries have caused significant damages to reinforced concrete (RC) structures, including RC bridges [1]. Previous studies demonstrated that RC bridge structures designed according to the traditional seismic codes controlling the ductile inelastic structural response during major earthquakes may suffer extensive structural damage after a design level earthquake, along with possible substantial maximum and residual deformations [2–4]. These damages and large residual deformations can significantly impede the post-quake rescue activities. Therefore, a recent thrust in performance-based earthquake engineering has led to the development of a large number of high-performance systems to improve the behavior of bridge structures subjected to severe earthquakes [5]. In particular, high-performance designs that consider more explicitly the ability of a structure to operate after it has experienced a severe earthquake are attracting more research attentions. Providing reliable mechanisms to dissipate the destructive earthquake energy and ensuring the safety of important structural members during the earthquake are the keys [6]. Among these mechanisms, buckling restrained braces (BRBs) have been widely used due to their exceptional energy dissipation capability and stable hysteretic behavior [7–9].

A BRB normally composes of a steel core, an encasing system and an unbounded material. The steel core is used to transmit the axial force, the encasing system prevents the core from global buckling under compression and the unbounded material and clearance are provided between the core and encasing system to ensure multiple-wave buckling of the steel core. BRBs are commonly designed as sacrificial members based on the structural fuse concept [10,11], which was firstly introduced by Roeder and Popov [12] for the eccentrically braced steel frames and further improved by Conner, Wada, Iwata, and Huang [13] after the 1994 Northridge earthquake. In this concept, the sacrificial element is designed to dissipate earthquake energy through the nonlinear hysteretic

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behavior, which in turn protects the more important bridge members such as bridge piers from severe damage, so that the bridge structure can be still in function after the severe earthquake. Due to the obvious advantages, BRBs have been extensively studied and widely used in engineering practices recently [14–17]. El-Bahey and Bruneau [18–20] added BRBs to a two-column bridge pier to increase the strength and stiffness of the pier. It was found that the seismic energy was dissipated through the hysteretic behavior of the brace, and the responses of bridge columns were kept in the elastic range. Bazaez and Dusicka [21] carried out large-scale experimental studies to investigate the cyclic behavior of a deficient RC bridge bent retrofitted with BRBs. Pseudo static tests and numerical simulations were carried out by Xie, Sun, and Wei [22] to investigate the seismic performance and energy dissipation capability of RC double-column piers with BRBs designed according to the structural fuse concept. These investigations demonstrated that BRBs as easily replaceable ductile braces could be implemented in both new and existing bridges. However, it is also noticed that because the post-yield stiffness of BRB is relatively low, the brace normally experiences large plastic deformation and is not able to return to its initial position after yielding; the structure is therefore vulnerable to concentrated damage and large residual deformation after a strong earthquake.

To overcome the drawbacks of traditional yielding systems and achieve a more resilient structure, different self-centering energy dissipation bracing (SCEB) systems that can undergo large axial deformation have recently been developed by different researchers. These proposed systems can provide stable energy dissipation capability and large restoring force to the main structure to enable the whole system have certain re-centering capability [23]. Zhu and Zhang [24–26] proposed an innovative SMA-based brace, where SMA wires were used to provide the restoring force and the steel blocks supplying frictions acted as the energy dissipating component. Christopoulos and Tremblay [27–29] presented another SCEB which consisted of a friction device and some prestressed tendons to provide the re-centering capability. Xu, Fan, and Li [30,31] developed a pre-pressed spring self-centering energy dissipation brace by combining the friction energy dissipation devices with pre-pressed disc springs. Herein, the friction devices between inner and outer tube members acted as the energy dissipation element and the combination disc springs were used to provide the self-centering capability. The experimental results indicated that the combination disc springs had sufficient stability of stiffness and strength and excellent self-centering behavior even after full compression. Some other self-centering braces combined with BRBs were also recently developed [32–34]. All these self-centering braces have demonstrated good energy dissipating ability and certain self-centering capability. However, there are still some shortcomings that should pay special attention to. For example, SMA is rather expensive and high-strength tendons may not have sufficient elongation capability in their elastic range to accommodate the required displacement. Moreover, most of these SCEBs were applied in the framed structures [27,35], their implementations in bridge structures have been rarely reported.

This paper develops an innovative self-centering buckling restrained brace (SC-BRB), combining a traditional BRB and pre-pressed combination disc springs, for seismic retrofitting of bridge structures. The traditional BRB system is used for energy dissipation and the disc spring is used to provide self-centering capability. Compared to the previous SCEB systems, the proposed SC-BRB system is cheaper and allows for larger deformation. The design of this novel system and its hysteretic performance are presented in Section 2. Large-scale experimental studies are carried out to examine the hysteretic behavior of the proposed system, and the results are presented and discussed in Section 3. This novel SC-BRB system is then applied to an example bridge structure with RC double-column bridge piers for seismic retrofitting. Nonlinear dynamic analyses are carried out to examine the seismic response of the example bridge structure retrofitted with the proposed SC-BRB system. The finite element (FE) model of the bridge is presented in Section 4 and the numerical results are discussed in Section 5. Both the experimental and numerical results are compared with the traditional BRB and self-centering brace (SCB) systems to demonstrate the performance of the proposed SC-BRB. Finally the concluding remarks of the present study are drawn in Section 6.

2. SC-BRB system

2.1. Proposed SC-BRB

Fig. 1(a) shows different components of the proposed innovative SC-BRB system. As shown, this system consists of a square outer steel tube, a group of disc springs, a rectangular inner steel tube, a steel core, four link stoppers, four blocking plates and two end plates. In which, the rectangular inner steel tube, steel core and end plates form the traditional BRB system. The steel core carries the axial load while the rectangular inner steel tube works as the encasing system and provides lateral confinement to the core and prevents global buckling. The stiffening ribs are welded to the non-yielding segment of the steel core to increase its stiffness and to further prevent local buckling in the non-yielding segments. A thin layer of unbounded material, which can be made of silica gel, is applied along the steel core to eliminate shear transfer during the elongation and contraction of the steel core and enables the steel core to contract and elongate freely within the inner steel tube.

The main components of the re-centering system include the square outer steel tube, disc springs, link stoppers and end plates. The right end of the square outer steel tube is welded to the right end plate, while the left end stays free. On the other hand, the left end of the rectangular inner steel tube is welded to the left end plates, while the right end keeps free. The pre-compressive disc springs are installed between the blocking plates that are welded to the two tube members to increase the self-centering ability. Once relative motion between the two tubes occurs, the pre-compressive disc springs can provide self-centering force to the system and bring the system to the initial position. Fig. 1(b) shows the different cross sections and Fig. 1(c) shows the schematic drawing of the main components of the proposed system.

2.2. Hysteretic performance of SC-BRB system

As can be seen from Fig. 1, the SC-BRB system can be regarded as a BRB system and a SCB system assembled in parallel. Therefore, the total hysteresis behavior of the SC-BRB system can be obtained by adding the hysteresis responses of the two systems together, as shown in Fig. 2. Fig. 2(a) shows the hysteretic behavior of a BRB system, in which k_{c1} and k_{c2} are the elastic stiffness and post-yield stiffness of the steel core, respectively; u_{cy} and f_{cy} are the yielding displacement and the corresponding yielding force of the steel core. Fig. 2(b) depicts the corresponding force-displacement relationship of a SCB system, where f_{sy} is the pre-compressive force in the disc spring; k_{s1} is the initial stiffness of the self-centering system, which is the total summation of the stiffness of the inner tube and outer tube; k_{s2} is the stiffness of the disc spring. The combined hysteresis behavior of the SC-BRB system is shown in Fig. 2(c), with δ representing the residual deformation when the brace is unloaded. As shown in Fig. 2(c), the hysteretic behavior of a SC-BRB system exhibits a typical flag shape.

To more clearly demonstrate how the SC-BRB system works, Fig. 3 illustrates the mechanics and the corresponding hysteretic