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Development and experimental verification of a pre-pressed spring self-centering energy dissipation brace

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ABSTRACT

The present study develops and experimentally verifies a new type of earthquake-resilient bracing system. The proposed pre-pressed spring self-centering energy dissipation (PS-SCED) bracing system combines friction energy dissipation devices between inner and outer tube members with a mechanism of pre-pressed disc springs that provides a self-centering capability and additional energy dissipation. Two large-scale PS-SCED braces with different types of inner tube members are designed, fabricated, and tested under low cyclic reversed loadings, and the results demonstrate that the PS-SCED braces exhibit stable and repeatable flag-shaped hysteretic responses with excellent self-centering capabilities, effective energy dissipation, large ultimate bearing capacity, and appreciable ductility. The residual deformation of the brace is controlled by adjusting the ratio of the initial pre-pressed force of the disc springs to the friction force provided by the energy dissipation devices. The energy dissipation and ductility of the PS-SCED brace constructed with a circular inner tube are better than those of the brace constructed with an X-shaped inner tube. A restoring force model for the PS-SCED brace is proposed, and the predicted hysteretic responses agree well with the experimental results.

1. Introduction

Although conventional earthquake-resilient structural systems designed and constructed according to current seismic design codes provide adequate safety and avoid structural collapse during earthquakes not exceeding their design parameters, they are subjected to large inelastic deformations that result in significant residual deformations after a strong earthquake. The extent of residual deformation is one of crucial factors determining the cost of structural repairs after an earthquake, and, when the residual deformation ratio is greater than 0.5%, the cost of repair will be greater than that of demolition and reconstruction [1]. Therefore, it is highly advantageous to develop earthquake-resilient structural systems with energy dissipation capabilities to reduce the structural damage and self-centering capabilities to reduce or even eliminate residual deformations occurring during an earthquake.

A truly earthquake-resilient structure has the capability of dissipating seismic energy, and also has self-centering capabilities that can return the structure to its initial position after an earthquake. Various earthquake-resilient systems with self-centering capacity have been proposed and verified by experiments. Rocking systems allow columns or walls to uplift at their bases during strong earthquakes, and self-centering is provided by gravity or pre-stressed elements [2,3]. Eatherton et al. [4,5] proposed a controlled rocking system comprised of vertical post-tensioning and energy dissipating fuses, and test results demonstrated that the system can sustain large earthquakes with minimal damage and eliminate residual deformations after load removal. Wada et al. [6] proposed the rocking wall system used in a retrofit project of the Tokyo Institute of Technology in Japan, and simulation results demonstrated that the system can better control the damage and failure modes of the structure after an earthquake. Pre-stressing technology is also used in beam-column assemblies for effectively eliminating residual deformations and increasing the deformation capacity of beams [7,8]. The dissipation of seismic energy is provided by the application of additional devices [9,10]. Buckling restrained braces (BRBs) have been widely used in recent years as structural elements owing to their high strength and energy dissipation capabilities. BRBs and BRB frames have been intensively studied by means of numerical simulations and experiments, and the results indicate that BRBs have good energy dissipation capabilities and stable hysteretic behaviors [11–18]. However, because a BRB is unable to return to its initial position after yielding, large residual deformations occur in BRB frame structures after a strong earthquake [19,20]. Nevertheless, BRB components or friction

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devices serving as energy dissipation members are often combined with high strength post-tensioned tendons or shape memory alloy (SMA) bars, both of which have been widely used to reduce structural deformation [21], and as connecting elements between beams and columns [22], and, thus, serve as self-centering members to provide adequate restoring force for the brace, resulting in braces with both energy dissipation and self-centering capabilities. Christopoulos et al. [23,24] proposed a self-centering energy dissipation brace that employed friction devices to dissipate energy, and a set of fiber-reinforced polymer tensioning elements to provide a self-centering capacity. Chou et al. [25–28] proposed a cross-anchored dual-core self-centering brace that employed an additional inner core and two sets of parallel post-tensioned elements to increase the deformation capacity. Miller et al. [29,30] proposed a new type of self-centering brace that employed SMA bars to provide restoring force and BRB components to dissipate energy. Ma and Cho [31] proposed a self-centering damper that employed pre-tensioned SMA wires and a roller system to provide high-energy dissipation and pre-compressed springs to supply an anticipated restoring force. Studies of hysteretic behaviors and seismic analyses have shown that structures comprised of self-centering braces exhibit smaller residual deformation than frame structures comprised of BRBs alone [32–37].

This paper presents a new type of bracing system developed to provide improved seismic behavior, and to reduce or eliminate the occurrence of residual deformation after earthquakes. The proposed pre-pressed spring self-centering energy dissipation (PS-SCED) bracing system makes full use of the special characteristics of combination disc springs to provide adequate restoring force and friction devices to dissipate energy. Disc springs can sustain large deformations without significant accumulations of residual deformation. As such, good self-centering and deformability can be achieved by the PS-SCED bracing system, which allows the present limitations in deformability and dimensions to be overcome. A large contact friction force between disc springs will result in small residual deformation; thus, the PS-SCED bracing system employs fewer disc spring segments for meeting both the strength and deformability requirements. Two large-scale prototype PS-SCED bracing systems with different types of inner tube members were designed, fabricated, and tested. A series of quasi-static tests and destructive tests were conducted to evaluate the hysteretic behavior and failure modes of the PS-SCED bracing systems, and comparative analyses of the energy dissipation and self-centering capabilities of the two specimens were also conducted. To further predict the hysteretic behavior, a restoring force model for the PS-SCED bracing system is proposed. Response results obtained using the proposed model are discussed and compared with the outcomes of the experiments involving the different PS-SCED bracing systems under various friction forces.

2. Configuration and behaviors of the PS-SCED bracing system

As illustrated in Fig. 1, the PS-SCED bracing system is comprised of two main bracing members, a self-centering member, and an energy dissipation mechanism.

The energy dissipation mechanism is comprised of a circular or X-shaped inner tube, a concentric box-shaped outer tube, eight friction devices and several blocking plates. The friction devices include contacting inner and outer plates that are respectively welded to the inner and outer tube members, and the inner plates of the friction devices are equipped with friction pads. The friction devices are activated when relative motion occurs between the inner and outer tubes, and the normal force required for generating a specified friction resistance between the inner and outer plates is provided by two pre-tensioned high-strength bolts. Washer plates are placed between the bolt heads and nuts to evenly distribute the normal force. Blocking plates are also respectively welded to the inner and outer tubes to provide a constant pre-pressed force to the disc springs. In addition, four rectangular steel plates are welded to the inner tube to enhance the stability of the PS-SCED bracing system.

The self-centering member is comprised of two groups of combination disc springs and several spring plates. The combination disc springs are compressed by free floating spring plates that are used to further compress the disc springs whether the brace is in tension or in compression. The combination disc springs are pre-pressed at an initial state, and the restoring force increases with increasing relative deformation between the inner and outer tube members, and, thus, ensures the self-centering capacity of PS-SCED bracing system.

The behaviors of PS-SCED bracing system in tension and in compression are illustrated in Fig. 2. When an external force P is less than the sum of the pre-pressed force of the combination disc springs, denoted as P_0, and the force required to activate the friction devices, denoted as F_0, no relative motion occurs between the inner and outer tubes, and the deformation of the bracing system δ is zero. Otherwise, when P is greater than the sum of P_0 and F_0, the two tubes slide past each other, and $\delta > 0$.

Meanwhile, the increasing restoring forces provided by the combination disc springs counteract the deformations between the tube members, and induce the system to return to its initial condition after unloading. Concurrently, the input energy is dissipated by friction.

The mechanical characteristics of the PS-SCED bracing system depend on a collaboration between the self-centering members and the energy dissipation mechanism. The total hysteretic behavior of the PS-SCED bracing system can be obtained by coupling these two bracing members, as shown in Fig. 3. Because of the contact friction between disc springs, the stiffness of the disc springs under unloading is less than the stiffness under loading, as shown in Fig. 3(a). When the brace is at rest, the bearing forces of the inner and outer tubes, respectively denoted as P_{in} and P_{out}, corresponding to the combination disc springs are given as

$$P_{in} = \frac{k_{in}}{k_{in} + k_{out}} \cdot P_0 \tag{1}$$

$$P_{out} = \frac{k_{out}}{k_{in} + k_{out}} \cdot P_0 \tag{2}$$

where k_{in} and k_{out} are the axial stiffness of the inner and outer tubes, respectively.

Once P is greater than the sum of P_0 and F_0, the relative motion between the inner and outer tubes activates the friction devices, and the stiffness of the PS-SCED bracing system changes from its initial elastic stiffness K_1, which is determined by the sum of the elastic stiffness of the two tubes and the combination disc springs, to its post-elastic stiffness K_2, which is determined by the stiffness of the combination disc springs, which is equal to k_s, and the activation displacement δ_0 can be calculated as

$$\delta_0 = \frac{P_0 + F_0}{K_1} \tag{3}$$

A non-dimensional parameter, denoted as ζ, useful for establishing the occurrence of residual deformation is then identified,

$$\zeta = \frac{2F_0}{F_0 + P_0} \tag{4}$$

A full hysteresis curve can be obtained by employing a sufficiently large value of ζ. While no residual deformation occurs when $\zeta \leqslant 1$, when $\zeta \geqslant 1$, the lower pre-pressed force induces the