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Development and experimental study of a self-centering variable damping energy dissipation brace

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ABSTRACT

A new self-centering variable damping energy dissipation (SC–VDED) brace is proposed to reduce the activation force and sudden change in stiffness after activation of self-centering energy dissipation braces. The brace uses the combination disc springs to provide self-centering capability and the structural design of a magnetorheological (MR) fluid device to realize variable damping energy dissipation. The mechanics of the SC–VDED brace and the equations governing its design and hysteretic responses are presented. A brace specimen with a total length of 1.365 m was designed and fabricated, and a series of cyclic tests were carried out under the sinusoidal excitation with different frequencies and amplitudes. Results demonstrate that the brace exhibits full quasi-flag-shaped hysteretic responses, a small activation force, few sudden change in stiffness, and large energy dissipation. The pre-pressed force of the combination disc springs should be larger than the initial damping force, and their stiffness should be increased to give full play to the self-centering and energy dissipation capabilities of the brace. Fatigue and destructive test results indicate that the behaviors of the brace are stable enough to provide self-centering and energy dissipation capabilities, and the loose and severe stress concentration of the outer tube clamps cause the brace to fail.

1. Introduction

Since earthquakes have caused increasingly serious losses and adverse impacts, a significant objective in civil engineering is to improve the seismic performance of structures, ensuring the safety of people and property. In recent years, earthquake resilient structures have been proposed, which have both reliable seismic behaviors and low costs for structural repair. The earthquake resilient structures can effectively dissipate earthquake energy and restore normal functions quickly after earthquakes. They contain earthquake resilient structural systems, such as rocking wall and self-centering frame, and earthquake resilient structural components that are replaceable and self-centering. Many researchers have studied self-centering energy dissipation braces made of various kinds of materials. These braces provide effective self-centering and energy dissipation capabilities for structures. Christopoulos et al. [1–6] proposed a self-centering energy dissipative steel brace that used friction devices to dissipate energy and pre-tensioned tendons for self-centering. Results of quasi-static brace system tests and dynamic full-scale frame validation tests indicated that the brace exhibits repeatable flag-shaped hysteretic responses and eliminates residual deformation. Zhu et al. [7–10] proposed a self-centering friction damping brace that employed super-elastic nitinol wire strands for self-centering and a friction effect for enhanced energy dissipation capacity. A nonlinear time history analysis of a three-story steel frame building with the braces showed that they can effectively control the seismic responses of frame building structures while minimizing their permanent drifts. Eatherton et al. [11–13] presented a self-centering buckling-restrained brace which used pre-tensioned super elastic nickel–titanium shape memory alloy rods to provide self-centering and additional energy dissipation capability. Test results showed that the system exhibits virtually no residual drift, and a brace with pre-tension force between 50% and 150% of the yield force can reliably recover the building while reducing the demands on the surrounding framing. Kitayama et al. [14–17] proposed a fluidic self-centering device which operates on principles similar to those of fluid viscous dampers but with the additional capability to provide self-centering force and stiffness. Study results demonstrated that buildings equipped with such devices experience a substantial reduction in residual story drift, peak story drift, peak floor acceleration, peak story shear, base shear forces and floor acceleration response spectra. Xu et al. [18–21] developed and experimentally verified a pre-pressed spring self-centering energy dissipation brace that employed friction devices to dissipate energy and

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pre-pressed disc springs for self-centering capability. Results of low cyclic reversed loading tests demonstrated stable and repeatable flag-shaped hysteretic responses with excellent self-centering and effective energy dissipation capabilities, large ultimate bearing capacity and appreciable ductility. Researchers have also used different energy dissipation and self-centering materials in a variety of proposed self-centering energy dissipation braces and dampers that have achieved good control during earthquakes [22–25].

The self-centering energy dissipation brace exhibits standard flag-shaped hysteretic responses, and the activation force of the brace is the sum of the damping force and pre-stressed force. The pre-stressed force is greater than the damping force to eliminate residual deformation. Because the damping force is constant, the activation force is usually large. At the same time, the sudden change in stiffness after activation of the brace greatly influences the total stiffness of the whole structure, and the non-linearity and the displacement amplification factor of structural responses can be reduced by decreasing the sudden change in stiffness of the brace [26,27].

In this paper, a new type of self-centering variable damping energy dissipation (SC–VDED) brace is proposed to reduce the activation force and sudden change in stiffness. Mechanics of the brace and working mechanism of the variable damping force are explained, and the equations governing its design and hysteretic responses are presented. A brace specimen with a total length of 1.365 m was designed and fabricated. Cyclic tests were conducted on the brace and the damping energy dissipation device to demonstrate their hysteretic characteristics, self-centering and energy dissipation capabilities under sinusoidal excitation with different frequencies and amplitudes. Fatigue and destructive tests were also conducted to evaluate the stability of the behaviors and the failure mode of the brace.

2. Configuration and mechanics of the SC–VDED brace

2.1. Configuration

As illustrated in Fig. 1, the proposed SC–VDED brace assembly consists of a force transmitting device, a self-centering device and a damping energy dissipation device. It uses the combination disc springs to provide self-centering capability, and the structural design of a magnetorheological (MR) fluid device to realize variable damping energy dissipation.

The force transmitting device is comprised of one inner tube, two outer tubes, two tube-end blocks, two inner tube blocks, two outer tube blocks and two connecting plates. The self-centering device includes the combination disc springs on both sides and four disc spring blocking plates. The damping energy dissipation device contains one piston, one cylinder, three permanent magnets, two sealing blocking plates and the MR fluid. The damping energy dissipation device is sealed by O-ring seals and sealing rings for the piston rod to avoid leakage. Mechanical connections, such as trapezoidal screw threads, clamps, and nested connections, are adopted to reduce residual stress and deformation caused by welding, as well as to fabricate the brace for more convenient mass flow production and long-term maintenance.

2.2. Variable damping mechanism

As a smart material, the MR fluid can reversibly change from a free flowing and linear viscous fluid to a semi-solid with controllable yield strength in milliseconds when exposed to a magnetic field. Because of the advantages in rapid response, large force capacity, low viscosity, good temperature stability and impurity insensitivity, many researchers have considered MR fluid dampers for civil engineering applications [28–31]. MR fluid dampers are divided into four categories: valve mode, shear mode, extrusion flow mode and shear-valve mode. The damping energy dissipation device of the SC–VDED brace is designed as shear-valve mode. The damping force f is the sum of the coulomb damping force f_c and the viscous damping force f_v, and is given as:

$$f = f_c + f_v = \frac{3L\tau_y}{h}A_p\mathrm{sgn}[v(t)] + \frac{12\eta LA_p}{\pi Dh^3}A_p v(t) \tag{1}$$

where L is the effective axial length of the piston, A_p is the cross-sectional area of the piston head, h is the gap width between the piston and cylinder, τ_y is the shear yield stress of the MR fluid, $v(t)$ is the velocity of the piston, η is the field independent post-yield plastic viscosity of the MR fluid, and D is the internal diameter of the cylinder.

According to Eq. (1), the coulomb damping force is a magnetic field intensity-related force, while the viscous damping force is velocity-related. If the magnetic field intensity, the performance parameters of the MR fluid, and the size of the piston are determined, the damping force f decreases with the increase of the gap width h between the piston and the cylinder. The shear yield stress τ_y increases as the magnetic field intensity increases, and also increases with decreases in the gap width h. In general, adjusting the gap width h is the main way to vary the damping force.

As the technical solution of the proposed brace, several grooves are set at the inner side of the cylinder, so that the gap width h changes with the loading or unloading of the brace, as shown in Fig. 1. At the beginning of loading, the gap width h is large, while the magnetic field intensity is small, so the initial damping force f_A is small. When continuing to load, the damping force f increases with the decrease of the gap width h. To obtain better energy dissipation capacity, an amplitude of the displacement, called a variable damping force region R, is designed, and the damping force maintains the maximum value f_{max} when the displacement exceeds the variable damping force region.

2.3. Mechanics principle and predictive model

The working principle of the SC–VDED brace is illustrated in Fig. 2. The inner tube and outer tubes are connected in series, and the tube-end blocks, inner tube blocks and outer tube blocks press the disc spring blocking plates to compress the combination disc springs for a self-centering capability. It means that the combination disc springs are always in a compressed state at each work stage. The brace is hinged to the structure to ensure an axial load, and the damping force of the MR fluid dissipates energy during earthquakes to reduce the structural vibration responses.

The work stages of the SC–VDED brace in tension or in compression are divided into seven parts, as shown in Fig. 3. When the external force is less than the activation force, displacement of the brace occurs because of the elastic deformation of the inner and outer tubes. The relative displacement of the piston and cylinder is still zero. This is the rigid loading stage where the response of the brace is linear, and the restoring force F can be given as:

$$F = k_1\delta \quad 0 \leqslant \delta < \delta_0 \text{ and } \delta\cdot\dot{\delta} \geqslant 0 \tag{2}$$

where k_1 is the combination stiffness of the inner and outer tubes, δ is the displacement of the brace, δ_0 is the activation displacement of the brace when loading, and $\dot{\delta}$ is the velocity of the brace.

When the external force exceeds the activation force, the relative displacement of the piston and cylinder occurs, and the response of the brace becomes non-linear. This stage is the variable damping force loading stage, and the restoring force is calculated as follows:

$$F = k_d(\delta-\delta_0) + P + f \quad \delta_0 \leqslant \delta < \delta_1 \text{ and } \delta\cdot\dot{\delta} \geqslant 0 \tag{3}$$

where P and k_d are respectively the pre-pressed force and stiffness of the combination disc springs, and δ_1 is the displacement of the brace when the damping force reaches the maximum value.

The brace continues loading, and the damping force maintains the maximum value. The restoring force at the ultimate damping force loading stage is obtained as follows:

$$F = k_d(\delta-\delta_0) + P + f_{max} \quad \delta_1 \leqslant \delta < \delta_{max} \text{ and } \delta\cdot\dot{\delta} \geqslant 0 \tag{4}$$