CYCLIC LOADING TESTS ON MULTI-DIRECTIONAL VIBRATION CONTROL SYSTEM BASED ON QUASI-PLANAR MOTION MECHANISM

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Abstract

For earthquake damage mitigation of structures, several types of vibration control systems have been developed. For example, structural vibration can be reduced by using energy dissipation devices such as steel dampers, where the seismic energy is dissipated through the yield deformation of steel. In axial-yield type dampers that use buckling-restrained braces, the bracing members require a sufficient second moment of inertia to prevent buckling under compression, as they are repetitively subjected to compressive and tensile forces. Recent studies proposed a new vibration control system for structures known as the seesaw system, where a pair of dampers is installed at both ends of the rotatable member. Based on the quasi-linear motion mechanism, only tensile forces are generated in the bracing members, which enables the use of steel rods and cables as bracing members. This system is effective for one directional vibration. Thus, multiple seesaw systems are necessary for controlling multi-directional structural vibration.

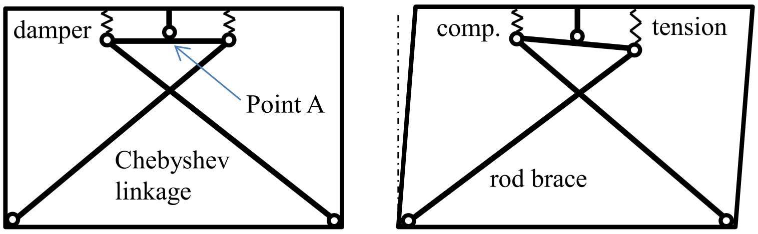
This study proposes a multi-directional vibration control system that uses a quasi-planar motion mechanism. The fundamental property of this system is that the bracing members remain elastic in tension during multi-directional vibration and it enables the use of steel rods and cables as bracing members. The energy dissipation property is examined through cyclic loading tests. The test specimen used in this study is a single story 3D model with a single bay for each direction. A rigid, square, steel plate is used as the roof floor and supported by four columns. The top and bottom ends of the column are connected using universal joints allowing the roof floor to move in all directions. The swinging plate is attached to four dampers and connected to the bottom plate using a universal joint. The damper is made from a steel plate that dissipates energy though flexural plastic deformation. Four bracing members connect the corners of the swinging plate and the roof plate, respectively, in such a way that the bracing members intersect each other. Three different loading directions were considered as experimental parameters. For gradually increasing loads, the lateral load was varied to increase the story rotation angle by 0.01, 0.02, 0.03, and 0.04 rad. For each rotation angle, two complete loading cycles were performed. The test results revealed that the proposed damping system is effective for multi-directional vibration control in structures.

Keywords: vibration control; multi-direction; steel damper; loading test; quasi-planar motion mechanism

1. Introduction

For earthquake damage mitigation of structures, several types of vibration control systems have been developed. Previous studies [1] investigated a vibration control system based on the quasi-linear motion mechanism, as shown in Fig.1. A Chebyshev linkage composed of three link members is included in this system. The point A shown in Fig.1(a) moves in an approximate straight line when the frame is deformed under lateral loads, as shown in Fig.1(b). A pair of dampers installed at the ends of the rotatable member exhibits compression and tension behavior to dissipate energy. This system is referred to as the seesaw system because the rotatable member moves in the same manner as a seesaw [2]. Only tensile forces are generated in the bracing members, which enables the use of steel rods and cables as bracing members. The benefits of using the seesaw system have been revealed in previous studies. The U-shaped steel dampers [1], steel slit dampers [3], and friction dampers have been examined through cyclic loading tests. The viscoelastic dampers [2] and fluid viscous dampers [4, 5] have been examined through seismic response analysis of the steel structures. The seesaw vibration control system is effective for one directional vibration of structures. Hence, multiple seesaw systems are necessary to control multi-directional structural vibration.

This study proposes a multi-directional vibration control system with a quasi-planar motion mechanism. The performance of the proposed system was examined through cyclic loading tests.

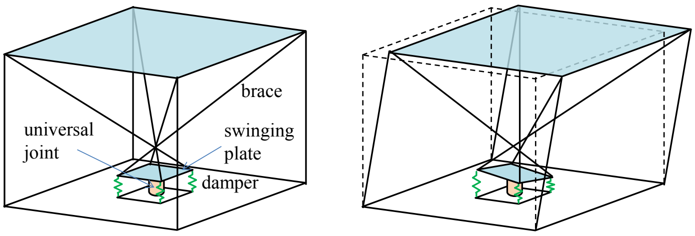


(a) Initial configuration (b) Deformed configuration

Fig. 1– Damping system based on the quasi-linear motion mechanism [1]

2. Damping system

The proposed damping system is shown in Fig.2. A swinging plate with four dampers is connected to the bottom floor using a universal joint. Four braces connect the corners of the swinging plate to those of the roof floor in such a way that the braces intersect each other. An effect of the quasi-planar motion mechanism enables multi-directional vibration control using a single damping device, as shown in Fig.2(b). This system enables braces to remain elastic in tension during vibration. Theoretical studies revealed that the lateral stiffness is constant in all directions.



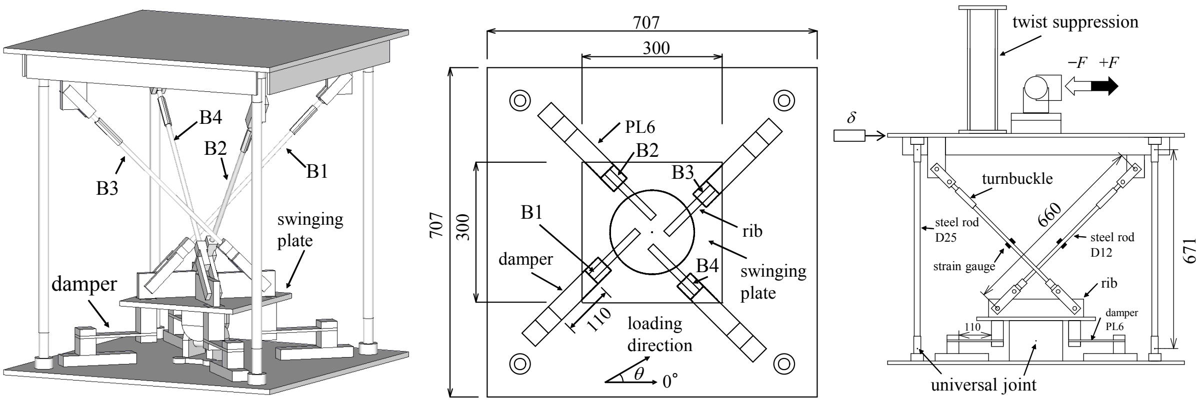
(a) Initial configuration (b) Deformed configuration

Fig. 2 – Proposed damping system based on the quasi-planar motion mechanism

3. Cyclic loading tests

3.1 Test specimen

The test specimen was a single story 3D model with a single bay for each direction, as shown in Fig.3. The roof floor was made of a rib-stiffened square steel plate that was supported by four columns. As the top and bottom ends of the column were connected using universal joints, the rigid roof floor was movable in all directions. Its twisting was suppressed by using a suppression member attached on the roof floor, as shown in Fig.3(c). This suppression member also worked as a restraint for out-of-plain movement. A swinging plate was connected on the universal joint fixed on the base plate. The four steel plate dampers with 110 mm length and 6 mm thickness were placed under the four corners of the swinging plate. The dampers were expected to dissipate energy though flexural plastic deformation. The four bracing members (B1, B2, B3, and B4) connected the corners of the swinging plate to the roof floor plate, respectively, as shown in Figs.3(a) and 3(b).



(a) Perspective view (b) Plan view (c) Diagonal elevation

Fig. 3 – Test specimen

3.2 Loading conditions and measurements

To reveal the characteristics of the multi-directional vibration control system, three loading directions of θ = 0°, 22.5°, and 45° were considered. The direction angle θ is defined in Fig.3(b). By using a turnbuckle, an initial pretension force of 10 kN was first introduced in each bracing. The lateral load F acting on the roof floor was varied to increase the story rotation angle R by 0.01, 0.02, 0.03, and 0.04 rad. For each rotation angle, two complete loading cycles were performed.

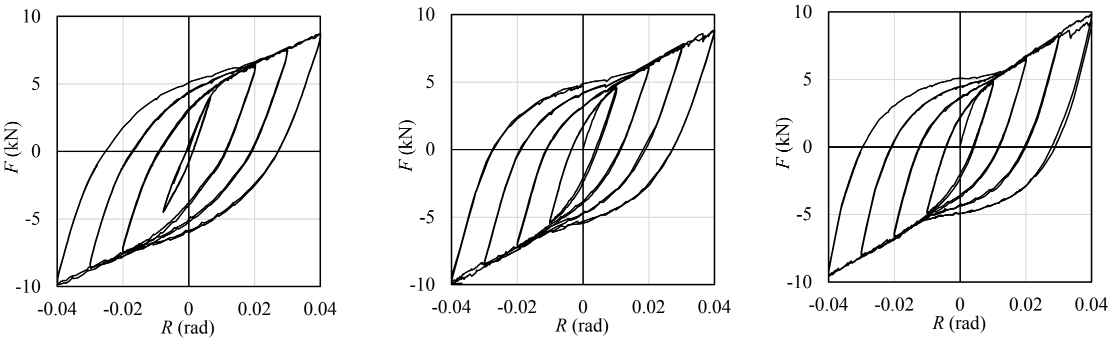
The lateral displacement δ of the roof floor in the loading direction was measured using a displacement sensor to obtain the story rotation angle R as δ / H, where H is the story height. The strain on each brace was measured using strain gauges to obtain the brace axial force N.

3.3 Test results

The test specimens were named as T-0, T-22.5, and T-45 corresponding to the loading directions of θ = 0°, 22.5°, and 45°, respectively.

3.3.1 Lateral load and story rotation angle relationships

In Fig.4, the relationship between the lateral load F and story rotation angle R is depicted. Overall, the hysteretic loop in each case exhibits a suitable shape for the hysteretic damper and reveals the applicability of the proposed system as a multi-directional vibration control system. The hysteretic loop shapes are slightly different from each other due to the difference in the damper deformation conditions. For T-0, all dampers deformed in a similar manner resulting in the common hysteretic loop shape observed for the ordinary hysteretic dampers. For T-45, by contrast, two dampers located in the loading plane deformed dominantly and the other two dampers in the perpendicular plane deformed slightly, which results in higher post yield stiffness. For T-22.5, the hysteretic loops exhibited an intermediate configuration between T-0 and T-45.

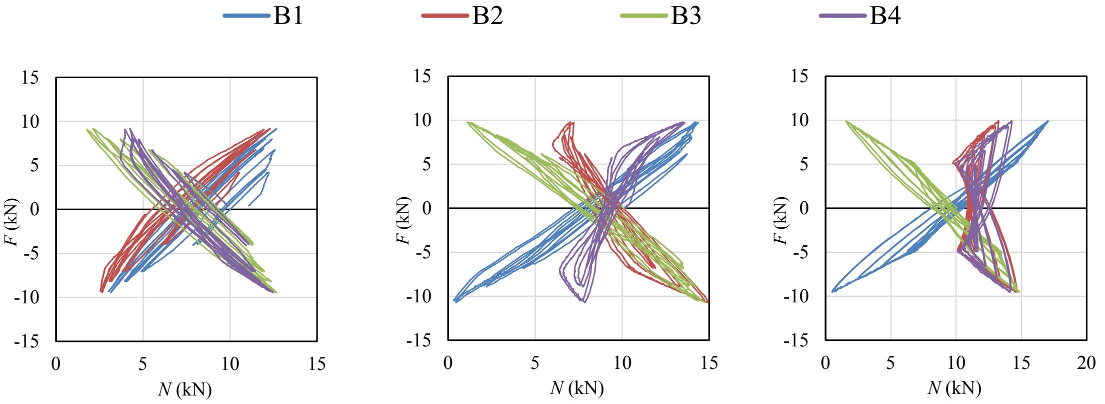


(a) specimen T-0 (b) specimen T-22.5 (c) specimen T-45

Fig. 4 – Relationship between the lateral load and story rotation angle

3.3.2 Lateral load and brace axial force relationships

In Fig.5, the relationship between the lateral load *F* and brace axial force *N* is shown. The brace axial force varies around 10 kN, which is the initial pretension force. For T-0, the axial forces of B1 and B2 had similar values. Also, those of B3 and B4 had similar values that varied in an opposite manner to B1 and B2. For T-45, the variation of the brace axial forces was larger than those of B2 and B4 because the braces B1 and B3 were located in the loading plane. For the large lateral load range, the brace axial forces of B2 and B4 increased to some extent. For T-22.5, the variation of the brace axial forces of B2 and B4 was larger than that of T-45. For all cases, the brace axial force was elastic on the tension side; even for the large story rotation range, which is a peculiar characteristic of the proposed system. This enables the use of steel rods as braces to obtain good hysteretic loops without slippage.

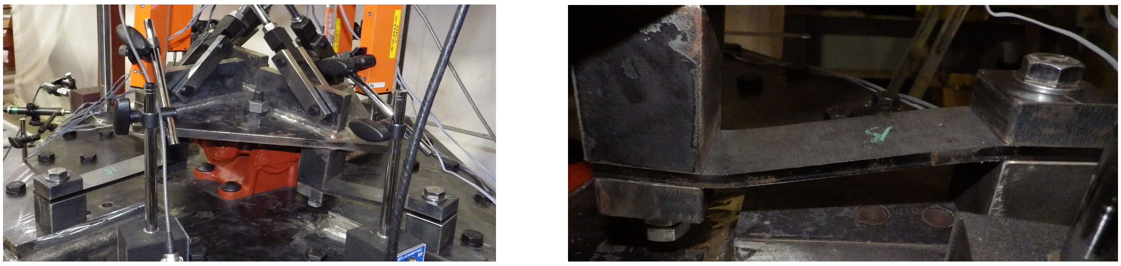


(a) specimen T-0 (b) specimen T-22.5 (c) specimen T-45

Fig. 5 – Relationship between the lateral loads and brace axial force

3.3.3 Deformation at the final stage of loading

In Fig.6, the deformation of the specimen T-45 for R = 0.04 rad is presented. It can be observed from Fig.6(a) that the tilt in the swinging plate resulted in the deformation of the lower-right damper. Fig.6(b) shows the damper deformation in which the plastic hinges form at both ends of the steel plate.



(a) Universal joint and swinging plate

(b) Steel plate damper

Fig. 6 – Deformation of T-45 for R = 0.04 rad

4. Conclusions

This study proposed a multi-directional vibration control system that uses the quasi-planar motion mechanism. The energy dissipation performance of the proposed damping system was examined through cyclic loading tests. The test specimens were subjected to three different loading directions of $\theta = 0°$, 22.5°, and 45°. The hysteretic loops revealed the efficacy of the proposed system as a multi-directional vibration control system.

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