Cyclic behavior of moment-resisting frames strengthened with steel curved dampers

H L Hsu¹ and H Halim¹
¹ Dept. of Civil Engineering, National Central University, Taoyuan City, Taiwan

hhsu@ncu.edu.tw

Abstract. Steel moment frames have been widely used for earthquake-resistant purposes. These systems possess significant ductility, however, excessive deformation due to the lower structural stiffness. In order to improve the behavior of moment-resisting frames when subjected to cyclic loads, a new design that combined steel curved damper and brace member was proposed in this study. The curved damper was cut from steel plate and was placed in the center portion of the brace member. The new device was attached to the frame and was used to dissipate energy throughout the load application. A series of loading tests on steel frames strengthened with the proposed design were carried out. The strength and energy dissipation capabilities of frames with and without the strengthening device were compared. It was found from the comparisons that the behavior of framed structures was significantly improved, thus justified the effectiveness of the proposed design.

1. Introduction
Steel moment frames have been widely used for earthquake-resistant purposes [1-3]. These systems possess significant ductility, however, excessive deformation due to the lower structural stiffness. Application of brace members to the steel moment frames has been considered effective approach to reduce the excessive deformation, as structural stiffness can be significantly enhanced. This approach subsequently raises concerns in loss of structural deformability due to excessive structural stiffness and buckling of brace member at large deformation [4-5]. Therefore, a remedy, i.e. development of a brace with adequate stiffness and deformability simultaneously, to further improve the structural behavior is essential. It has been investigated in the authors’ previous study [6] that when steel plate was fabricated in curved shape and loaded by in-plane bending, the device would exhibit sufficient strength, sustained stability at large deformation and dissipated significant energy through inelastic deformation. This device was named steel curved damper, as shown in Figure 1. To further improve the behavior of moment-resisting frames when subjected to cyclic loads, a new design that combined steel curved damper and brace member, forming A-Brace as shown in Figure 2, was proposed in this study. The curved damper was placed in the center portion of the brace member and mobilized by the lever mechanism of the A-Brace. The new device was attached to the frame and was used to dissipate energy throughout the load application. A series of loading tests on the steel curved dampers and steel frames strengthened with the proposed design were carried out. The strength and energy dissipation capabilities of frames with and without the strengthening device were compared to evaluate the effectiveness of the proposed method.
Steel curved damper was cut from steel plate with desired geometry. As shown in Figure 1, the maximum eccentricity between the center point of the damper and the axis that connecting the two ends, i.e. $\Delta$, will cause extra moment ($P\Delta$) when subject to axial load $P$. In this regard, the maximum stress at the center point of the curved damper can be evaluated by the following equation [6]:

$$\sigma_{max} = \frac{M}{I} + \frac{P}{A} \quad (1)$$

In which, $d$ and $t$ are the damper depth and thickness, respectively.

Since the curved damper was bent about the strong axis of the plate, the above-mentioned stress can be further expressed as follow:

$$\sigma_{max} = \frac{P\Delta}{\frac{1}{2}dt} + \frac{P}{dt} \quad (2)$$

Therefore, the strength of steel curved damper ($P_{SCD}$) that will cause yielding of curved damper, can be obtained when the maximum stress was equal to the plate yielding stress

$$P_{SCD} = \frac{dt\sigma_y}{6d+dt} \quad (3)$$

Figure 3 shows the strength of steel curved damper, $P_{SCD}$, with various eccentricities. It can be found from the figure that damper with larger eccentricity will incur lower strength.
3. Evaluation of frame performance

As mentioned in earlier section, the structural behavior would be improved by the application of the proposed A-Brace. To evaluate the effectiveness of the proposed method, the design and load-resisting mechanism of the A-Brace must be investigated. The A-Brace is composed of steel curved damper (SCD) and two rigid members. The two members were used to transmit force from brace to damper, therefore should be designed to remain elastic at the ultimate strength level.

As shown in Figure 2, the length of beam, height of column, length of brace and length of intersections between axes of SCD and A-Brace can be represented by \( L_b, L_c, L_{br}, \) and \( L_i \), respectively. The strength relationship between A-Brace (\( P_{br} \)) and steel curved damper (\( P_{SCD} \)) can be described using the following equations:

\[
P_{br} = \frac{L_i}{L_{br}} P_{SCD}
\]

(4)

For adequate design, the damper strength should be determined not to damage the brace member. The typical hysteretic behavior of A-Brace, evaluated by ANSYS [7], can be seen in Figure 4. It can be found from the figure that the strength of A-Brace in compression and tension is slightly different. This is due to the changing of eccentricity of curved damper during various deformation load. Nevertheless, the A-Brace exhibited improved stable behavior over the tradition braceS, under tension and compression.

4. Experimental verification

4.1. Test Specimens

Four test frames including one moment frame and three strengthened frames, as listed in Table 1, were fabricated to investigate the effectiveness of A-Brace as strengthening scheme. The detail of test frame can be seen in Figure 5. The columns and beams were made of SN400 H250x250x9x14 and H175x175x7.5x11, respectively. A strengthened panel zone in the beam-column joint was applied by adding 10 mm plate to prevent shear failure in this area. 30-mm-thick steel curved damper with length equaling 700mm was attached to the center region of A-Brace. Depths of curved dampers were 120 mm, 100 mm and 90 mm, respectively. The test frames were labeled according to the size of damper.
geometry. For example, AF 120x30 indicated a steel moment frame equipped with A-Brace and curved damper with depth and thickness equaling 120 mm and 30 mm, respectively. Each test frame was loaded by a servo-controlled hydraulic actuator under a series of cyclic displacement commands according to FEMA 461 [8] protocol until 5% story drift ratio.

| Specimen | Depth d (mm) | Thickness t (mm) |
|----------|--------------|------------------|
| MF       | N.A          | N.A              |
| AF 120x30| 120          | 30               |
| AF 100x30| 100          | 30               |
| AF 90x30 | 90           | 30               |

Table 1. Details of test specimens.

Figure 5. Detail of test frame.

4.2. Results and comparisons

Failure pattern of frame with A-Brace is shown in Figure 6. It was observed from the test that the failure began with the yielding in the inner side of the curved damper. Further observations validated that no fracture or damper plate buckling was developed during the loading process thus proving the ductility and stability of the damper. The hysteretic loops for all test frames are shown in Figure 7. It can be found from the figure that all frames exhibited stable behavior when the frame story drift reached 5% with no degradation in performance. Higher strength can be achieved when A-Brace is attached to the steel moment frame. The strength improvement of the frame after adding A-Brace can reach up to 2.31 times. Frame strength and energy dissipation were further correlated and shown in Figure 8. It can be found from the comparison that significant energy dissipation gain was achieved, for example, 1.94 times in frame AF 120x30 than that of the moment frame, when the proposed device was adopted. These phenomena validated the effectiveness of the proposed method to structural strengthening design.

Figure 6. Typical failure pattern of frame with A-Brace.
5. Conclusions
This study investigated the behavior of steel curved damper and its applicability to structural strengthening. A series of loading tests on steel frames strengthened with the proposed design were carried out. It was found from the tests that all frames exhibited stable behavior when the frame story drift reached 5% with no degradation in performance. Strength improvement of the frame after adding A-Brace can reach up to 2.31 times. Further comparison on the test results showed that significant energy dissipation gain was achieved, for example, 1.94 times in frame AF 120x30 than that of the moment frame, when the proposed device was adopted. Simultaneous enhancement in strength and energy dissipation validated the effectiveness of the proposed method to structural strengthening design.

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