Cyclic Loading Tests Of Steel Dampers Utilizing Flexure-Analogy of Deformation

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SUMMARY
Steel dampers utilizing flexure analogy of deformation are proposed for seismic retrofit of existing buildings. Proposed dampers transform forces acting on the pin-connection into bending moment resisted by three parallel struts, among which two is to resist bending moment and the other one is to resist axial force. Cyclic loading tests were conducted for four types of specimens in order to evaluate their strength and deformation capacities. All specimens showed stable hysteretic loops with cumulative plastic deformations meeting AISC/Seismic Provisions. However, the ultimate deformation capacity of the dampers needs improvement to accommodate reasonable design story drift ratio higher than 1 %.

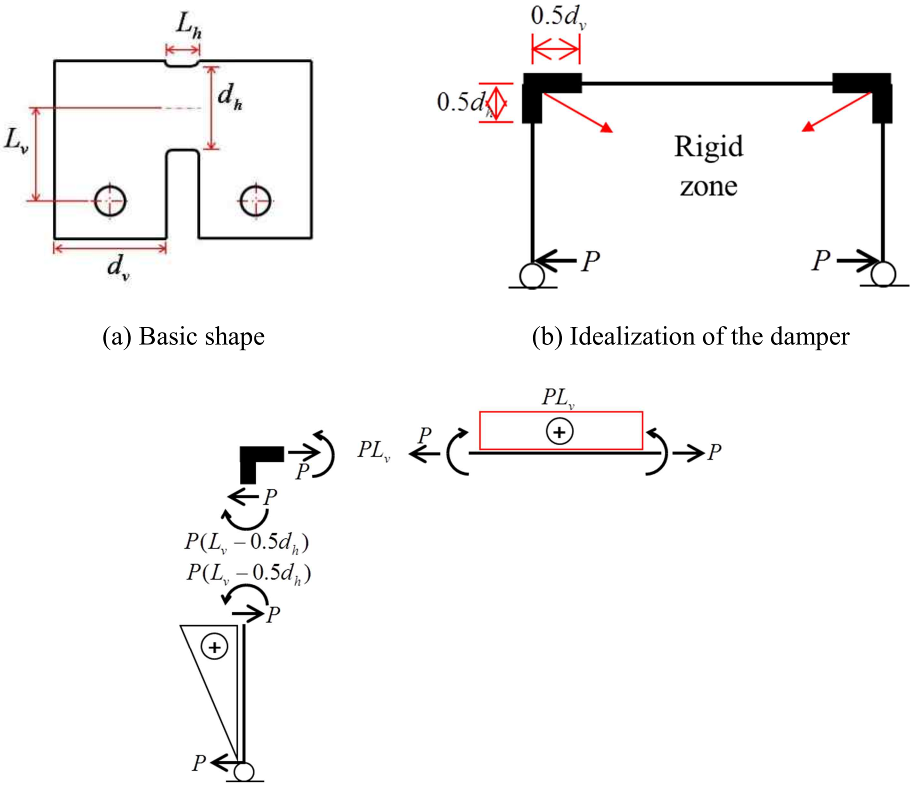
Keywords: steel damper, cyclic loading test, seismic retrofit

1. INTRODUCTION

Many kinds of dampers have been developed and applied to the design of new buildings and retrofit of existing ones successively. Most structural design codes have provisions related to the design of the dampers. Among various types of the dampers, the steel dampers are displacement dependent dampers that dissipate energy by yielding of the steel materials of which occurrence depends on the displacement response. Steel dampers need to have a sufficient deformation capacity so that they provide stable energy dissipation without buckling or fracture during earthquakes. Well-known steel dampers are ADAS system, TADAS system, slit-plate damper, buckling-restrained brace, etc. They utilize various types of the deformation such as bending, shear and axial deformations. The performance of those steel dampers were verified by experimental tests, and applied to the many actual projects for new and existing buildings (Oh and Chang, 2000; Soong and Spencer, 2002; Ookouch and Takeuchi, 2006; Ricky et al., 2008; Symans et al., 2008; Lee et al., 2009).
In this study, steel dampers utilizing deformation analogous to flexure are proposed for seismic retrofit of existing buildings. Proposed dampers have a shape of a simple portal frame, which is composed of a beam and two columns and made of a steel plate. This configuration of the dampers transform forces acting on the pin-connection into bending moment and axial force resisted by a short beam-column type member. Cyclic loading tests were conducted for four types of the specimens with different strength and stiffness in order to examine the deformation capacity and the theoretical equations on the strength and deformation. The test results are evaluated based on AISC/Seismic Provisions (AISC, 2006).

2. BASIC CONCEPT THE PROPOSED DAMPERS

This study proposes steel dampers made of common structural steel materials. The proposed dampers have a basic shape of portal frames composed of relatively thick members as illustrated in Figure 1 (a) and can be idealized as Figure 1 (b), in which the damper is supported by two rollers and two horizontal forces act on those supports. This damper is designed to inelastic deformation occurs in the horizontal member. In accordance with the statics, the horizontal member is under a uniform bending moment throughout its length in this configuration so that every part of this member contributes to the energy dissipation uniformly, as illustrated in Figure 1 (c). The two vertical members need to be designed to provide sufficient elastic stiffness and to restrict yielding within the horizontal member.



(a) Basic shape (b) Idealization of the damper

(c) Distribution of the bending moment

Figure 1. Concept of the steel dampers utilizing flexure-analogy of deformation

Those dampers provide the primary structures with additional energy dissipation, additional stiffness, and strength. The proposed dampers can be installed in existing moment frame structures by chevron type brace as illustrated in Figure 2 (a) and this kind of frame unit can be attached to the outside of the exterior frame of the building as shown in Figure 2 (b).

The yield strength of the damper is defined as the horizontal force when the bending moment of the horizontal member reaches the plastic moment. The horizontal member has an axial force equal to the external horizontal force P, which needs to be taken into account in the calculation of the plastic moment. The ultimate strength of the damper can be calculated by modifying the yield strength using the ratio of the ultimate stress to the yield stress of the steel material. The expressions for the yield strength and the ultimate strength are given, as follows.

$$P_y = \frac{M_p}{L_v} = A_p f_y \tag{1}$$

$$P_u = P_y \frac{f_u}{f_y} \tag{2}$$

where P_y is the yield strength, and P_u is the ultimate strength, M_p is the plastic moment of the cross section, L_v is the length of the vertical member, and f_y and f_u are the yield and ultimate stresses of the material, respectively. The deformations corresponding to both strengths are expressed by the following expressions.

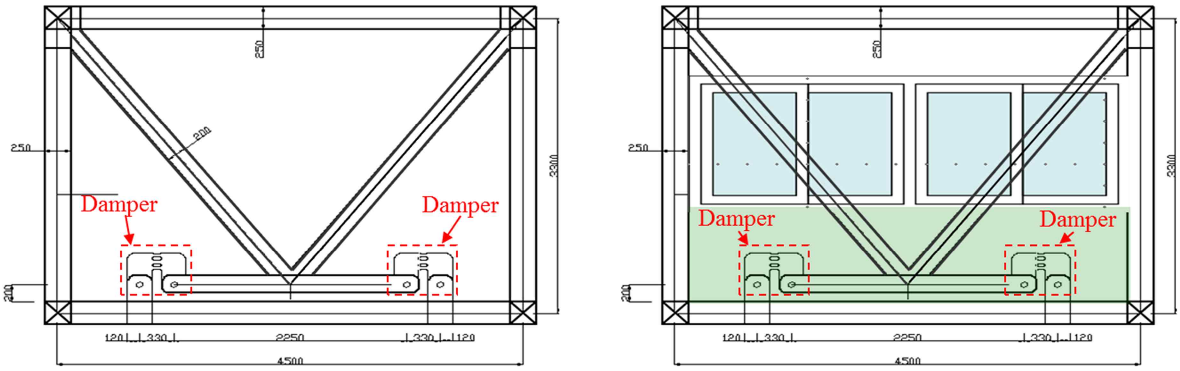
$$\Delta_y = \Delta_{yo} \cdot \frac{P_y}{P_{yo}} \tag{3}$$

$$\Delta_u = \Delta_{uh} + 2\Delta_{uv} \tag{4}$$

with

$$\Delta_{yo} = \Delta_{yo,h} + 2\Delta_{yo,v} \tag{5}$$

where Δ_y and Δ_u are the yield and ultimate deformations, respectively, and Δ_{yo} $\Delta_{yo,v}$, $\Delta_{yo,h}$ and P_{yo} are the deformation of the damper, the deformation of the vertical member, the deformation of the horizontal member, and the strength of the damper, respectively, corresponding to the initial yielding at the extreme fiber of cross section for the horizontal member, respectively. Δ_u, Δ_{uh} and Δ_{uv} are the ultimate deformation of the damper, the component of the ultimate deformation corresponding to the deformation of the horizontal and vertical members, respectively.



(a) Unit system of the braced frame with the proposed dampers

(b) Unit frame attached to the exterior frame of a building

Figure 2. Installation of the proposed dampers

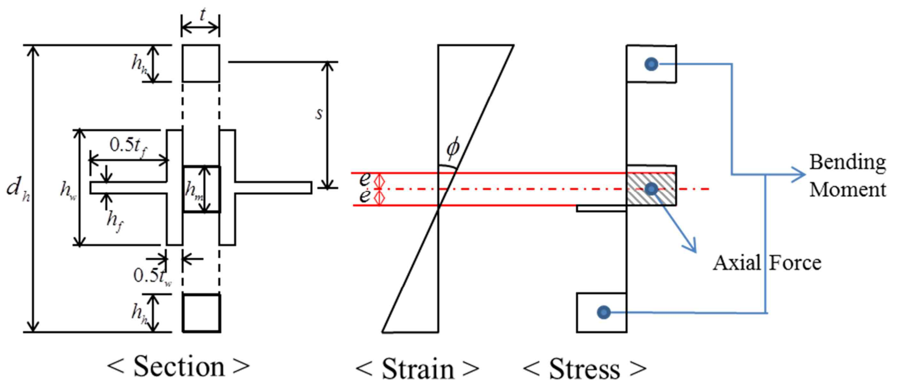
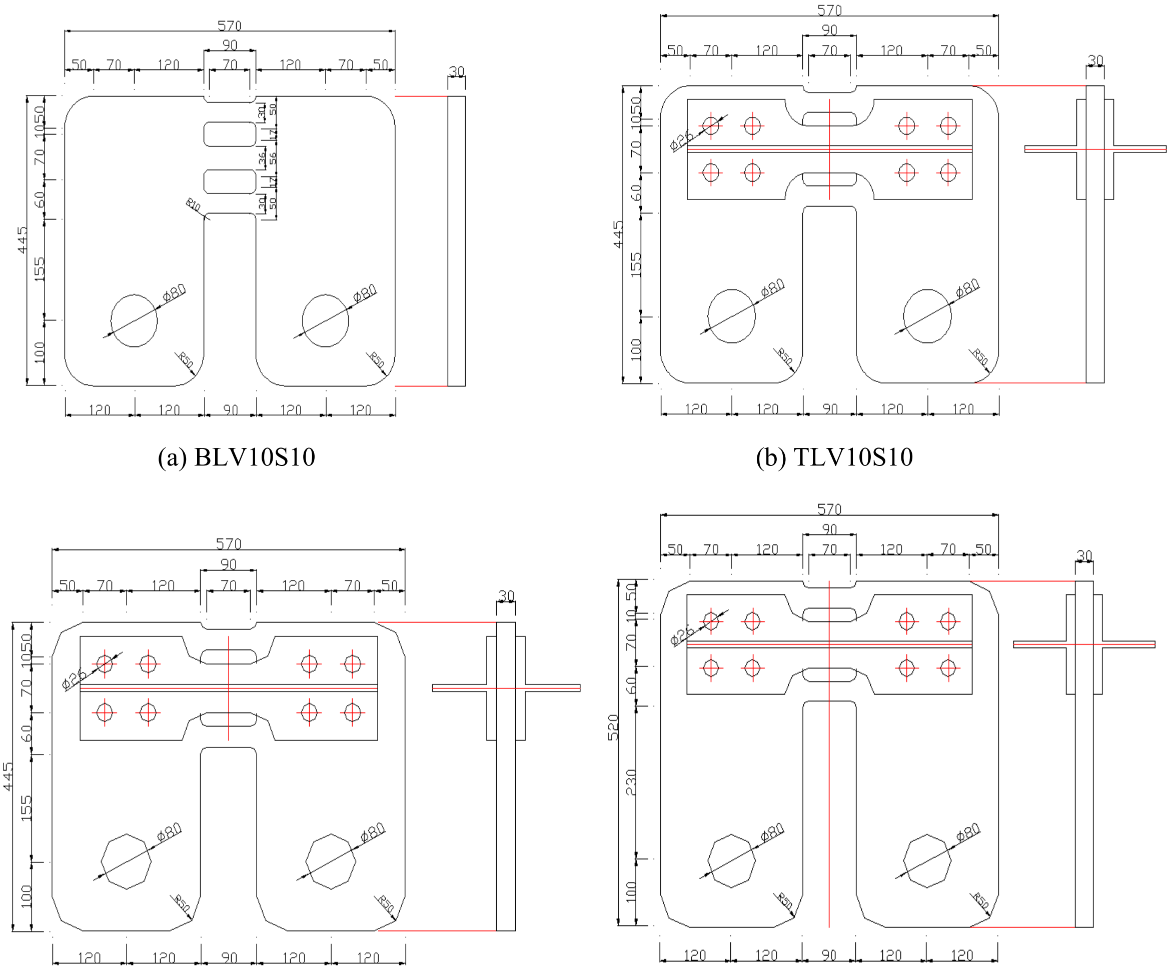


Figure 3. Cross section, strain and stress distribution of the horizontal member

3. DETAILS OF SPECIMENS

Metal yield dampers are usually designed to have high stiffness and low strength so that they yield earlier than the primary structures. The cross section of the horizontal member for the proposed dampers needs to be designed to have higher moment of inertia and low plastic moment if possible. The moment of inertia of a cross section and the plastic moment are proportional to the square of the distance and the distance itself, respectively. Therefore, eliminating the central region of the horizontal member helps to realize this condition. However, the horizontal member does not only have to resist the bending moment but also the axial force that are formed by the normal stress in the central region of the cross section. Considering this role of the central region in the horizontal member, regions between the central region and the end region on the cross section were removed. As a result the horizontal member has the section illustrated in Figure 3. If we assume the plane section remains plane, the distribution of the strain and stress can be represented as illustrated in Figure 3. The yield and ultimate strengths and corresponding deformations are estimated based on those strain and stress distribution and compared with the experimental ones in the subsequent sections.

Four types of the proposed dampers are designed for the cyclic loading tests and illustrated in Figure 4. Each vertical member of the test specimens has a ϕ80 hole for hinged connection. Two specimens are produced for each type of the damper. BLV10S10 is the basic type composed of single plate with the thickness of 30 mm. The length of the horizontal members is 90 mm, which is the clearance between the two vertical members. The length of the vertical member is 250 mm from the center line of the middle horizontal number to the center of the hole. Horizontal center-to-center spacing of the separated horizontal member is 33.5 mm. The depth of the middle horizontal member is 36 mm and those of the upper and lower horizontal member is 30 mm. More cross section is assigned to the middle member, because the middle member should bear the axial force stably. Other three types TLV10S10, TLV10S14, and TLV13S10 are composed of the main plate and two T-shapes, which are attached with 4 bolts and nuts at each end in order to prevent out-of-plane bending of the main plate. TLV10S10 has the same main plate as BLV10S10 with the T-shapes attached. TLV10S14 has the center-to-center spacing increased by 43 % compared to TLV10S10 with other conditions the same. TLV13S10 has vertical members that are 10% longer than those of TLV10S10 with other conditions the same. The shapes and dimensions of all the four types of the damper specimen are illustrated in Figure 4.



(a) BLV10S10 (b) TLV10S10

(c) TLV10S14 (d) TLV13S10

Figure 4. Shape and dimensions of the specimens

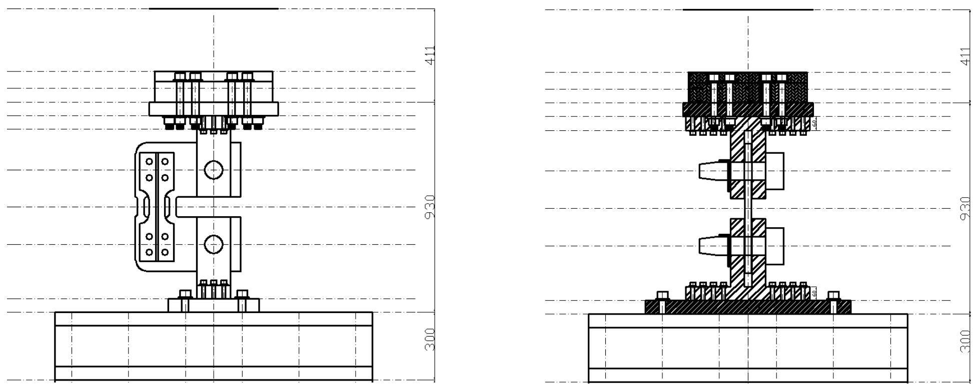
SS400 steel is used for the proposed damper considering economic feasibility, although low strength steel is more appropriate for metal dampers. Coupon tests based on KS B 0801 1A were performed for each three specimens taken from the main plates, the web and flange of the T-shapes, respectively, and the results are listed in Table 1.

Table 1. Coupon test results of the material

Place of the specimen	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)	Elongation (%)
Main plate	255.67	417.67	198667	32.33
Flange of the T-shapes	295.67	451.67	207333	29.33
Web of the T-shapes	336.00	460.67	212667	28.67

4. TEST SETUP

Test setup for the cyclic loading tests is illustrated in Figure 5. The specimens were placed in the 2000kN universal testing machine of which loading direction is vertical. The vertical displacement was controlled using the typical loading sequence plotted in Figure 6, in which the maximum displacement corresponds to the 1% story drift ratio for the typical school buildings in Korea. However, different loading sequences were applied to two specimens TLV10S10, because the increment of the displacement amplitude for the whole specimens was determined in the test of TLV10S10 by trial and error method.



(a) Front (b) Side

Figure 5. Typical test setup for specimens

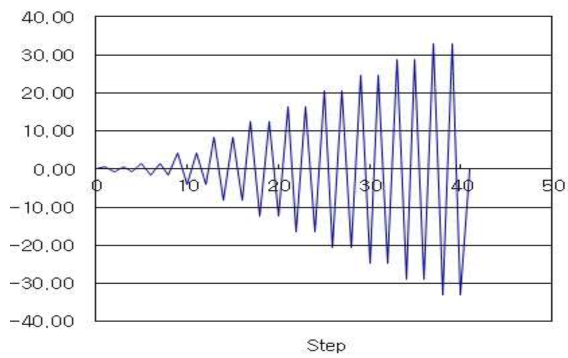
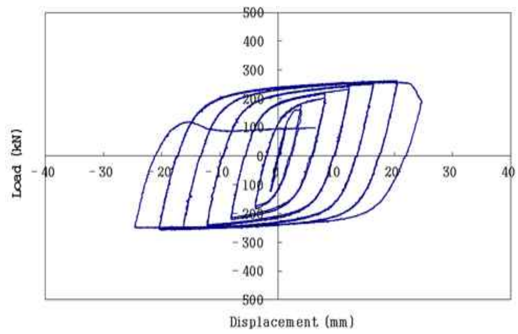


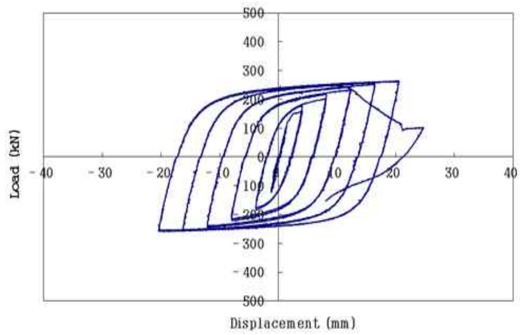
Figure 6. Typical sequence of loading

5. LOAD-DEFORMATION RELATIONSHIP

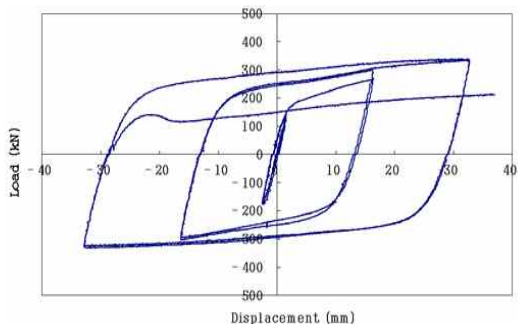
Load-displacement curves for all the eight specimens are plotted in Figure 7. Each specimen shows a stable hysteresis curve until it reaches the point of peak strength with continuous increase of strength due to the Baushinger effect. The load-deformation curve for the two TLV10S10 type specimens have a less number of cycles, because it was utilized to determine the increment of the displacement amplitude by trial and error as mentioned earlier. Most specimens fractured at the lower horizontal member with a necking phenomenon accompanied. The T-shaped stiffener slips so early that its contribution to the stiffness and strength was limited, which can be confirmed by comparing Figure 7 (a) and (b) for the BLV10S10 specimen without stiffeners with Figure 7 (c) and (d) for the TLV10S10 specimen, of which both types have the same center plate.



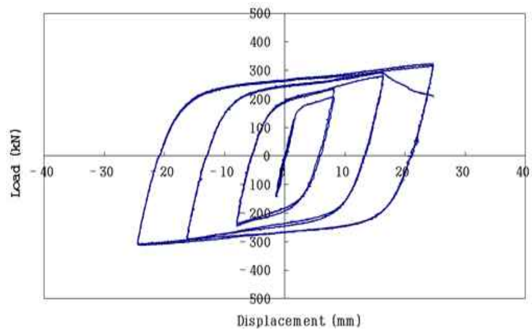
(a) BLV10S10 specimen 1



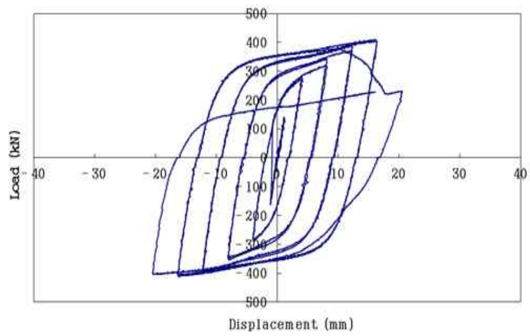
(b) BLV10S10 specimen 2



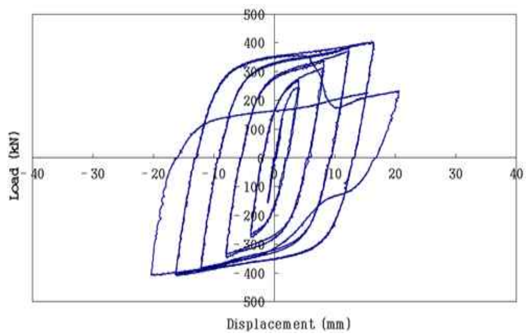
(c) TLV10S10 specimen 1



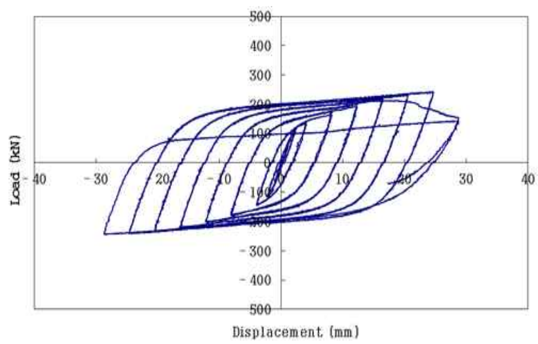
(d) TLV10S10 specimen 2



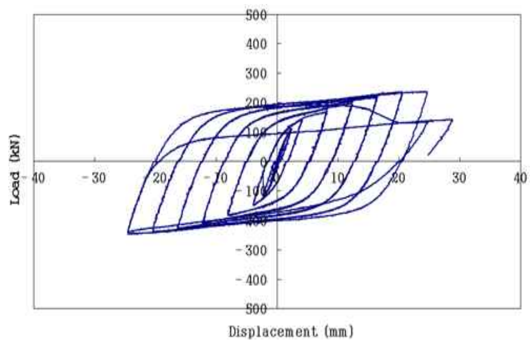
(e) TLV10S14 specimen 1



(f) TLV10S14 specimen 2



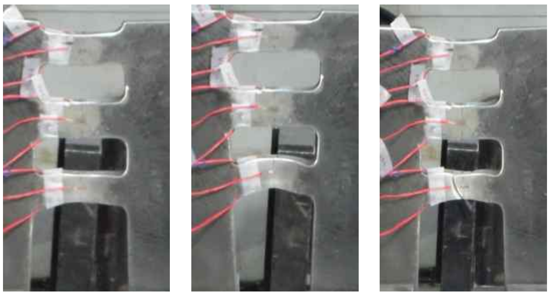
(g) TLV13S10 specimen 1



(h) TLV13S10 specimen 2

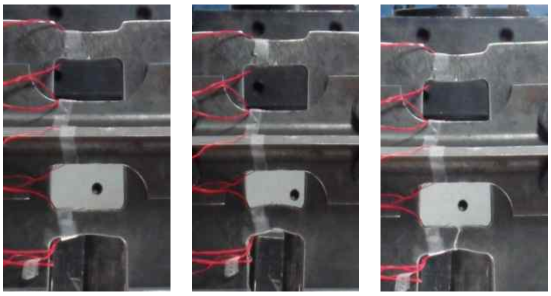
Figure 7. Load-displacement curve for each specimen

In the two BLV10S10 specimens, which are the basic type for all the specimens, necking of the lower horizontal member occurs at the first cycle for the amplitude 20.62 mm. Then, the lower member fractured at the first cycle of the amplitude 24.75 mm in tension with strength degradation. In the TLV10S10 specimens, necking of the lower horizontal member occurs at the first cycle for the amplitude 24.75 mm. Then, the lower member fractured at the first cycle of the amplitude 33 mm in tension with strength degradation. In the TLV10S14 specimens, necking of the lower horizontal member occurs at the first cycle for the amplitude 16.5 mm. Then, the lower member fractured at the first cycle of the amplitude 20.63 mm in tension with strength degradation. In the TLV13S10 specimens, necking of the lower horizontal member occurs at the first cycle for the amplitude 24.75 mm. Then, the lower member fractured at the first cycle of the amplitude 28.88 mm in tension with strength degradation.
Pictures for the peak tensile and compressive deformation and the fracture for the BLV10 S10 and TLV10S14 specimens are shown in Figure 8 and 9, respectively. Among those three horizontal members, the lower one undergoes the most bending in both tensile and compressive loadings on the dampers. In addition, the curvatures of those three horizontal members are significantly different, which can be confirmed with a visual check of both Figure 8 and 9.



(a) peak tensile deformation (b) peak compressive deformation (c) fracture

Figure 8. Horizontal members of BLV10S10



(a) peak tensile deformation (b) peak compressive deformation (c) fracture

Figure 9. Horizontal members of TLV10S14

6. STRENGTHS AND DEFORMATION CAPACITIES OF THE DAMPERS

Strength and deformation capacities of the specimens are listed in Table 2. Those capacities are obtained from the cycle that repeated two times without fracture. Values from each specimen and their averages are given in Table 2, where the values in the parenthesis are drift angle in percentages based on the typical story height of 3.3 m for school buildings in Korea. Although the TLV10S10 specimens have the highest deformation capacity, they have a less number of cycles compared to the other 6 specimens. Also, the existence of the stiffener has a minor influence to the deformation capacity of the dampers due to early slip. Therefore, it is rational to suppose that the TLV13S10 specimens have the best deformation capacity among the tested specimens. The cause of the better deformation capacity is seems to be caused by the longer moment arm length corresponding to the longer vertical members.

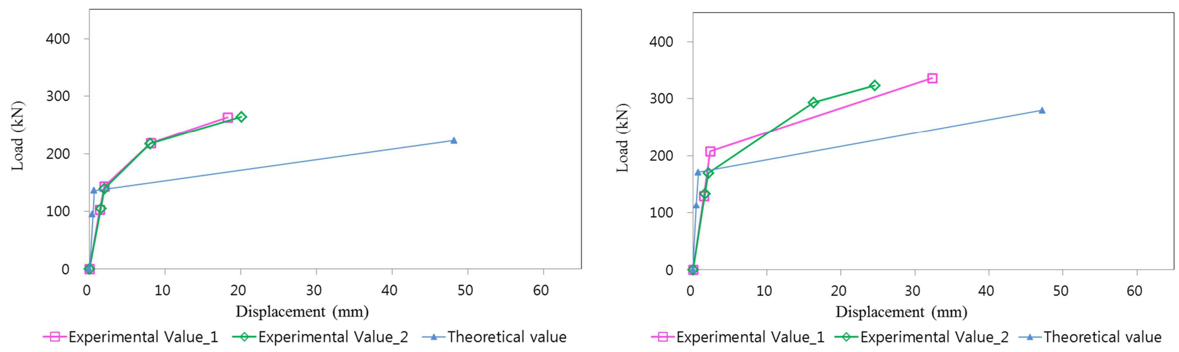
Table 2. Ultimate strength and peak deformation of the dampers (parenthesis: drift angle for 3.3 m story height)

Specimens	Average peak deformations (mm)		Average ultimate strengths (kN)	
	Tension	Compression	Tension	Compression
BLV10S10	20.63 (0.63%)	-20.63 (0.63%)	263.7	-259.1
TLV10S10	28.88 (0.88%)	-28.88 (0.88%)	328.6	-321.8
TLV10S14	16.5 (0.50%)	-16.5 (0.50%)	407.5	-410.7
TLV13S10	24.75 (0.75%)	-24.75 (0.75%)	240.5	-244.4

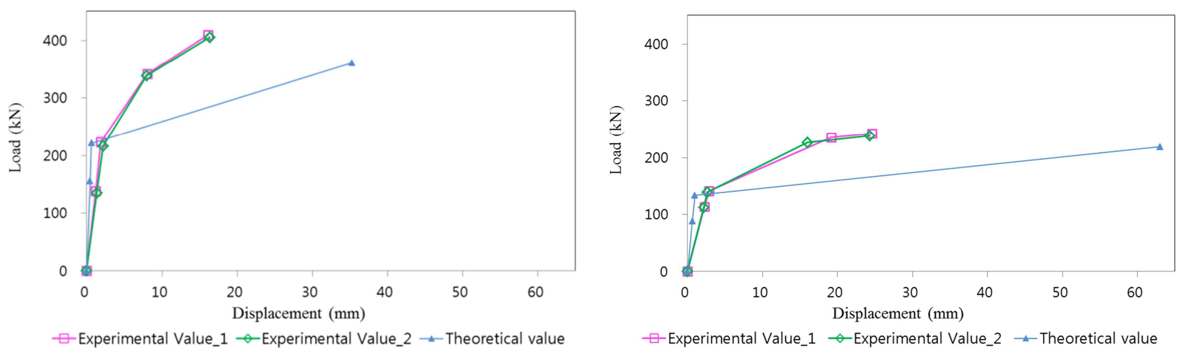
Cumulative inelastic deformations of the tested specimens are listed in Table 3. AISC/Seismic Provisions for Structural Steel Buildings (AISC, 2006) requires the cumulative inelastic deformations are at least 200 times of the yield deformation. All the inelastic deformations in the Table 3 are hihger than 200 times of the corresponding yield deformations. However those provisions have the additional requirement that the deformation capacity must be higher than 1.5 times of the design story drift ratio of which minimum value is limited to 1%. Therefore the peak deformation capacity must be higher than 1.5 % drift ratio of the buildings. However, all the peak deformation capacities given in the Table 2 are lower than 1.5%. So, the proposed dampers need to be improved in order to increase their deformation capacities.

Table 3. Cumulative inelastic deformations

Specimens		Cumulative inelastic deformation (mm) (A)	Yield deformation (mm) (B)	A/B
BLV10S10	1	532.54	1.74	305.43
	2	531.96	1.60	333.33
TLV10S10	1	530.14	1.98	268.04
	2	528.88	1.80	294.27
TLV10S14	1	527.44	1.80	293.30
	2	525.47	1.61	327.16
TLV13S10	1	521.99	2.21	236.14
	2	519.17	2.15	241.15



(a) BLV10S10 (b) TLV10S10



(c) TLV10S14 (d) TLV13S10

Figure 10. Force-displacement envelope of the test specimens

The force-displacement envelopes obtained from the tests and the theoretical equations given by Eq. (1) to (5) are compared in Figure 10. Considerable differences in the initial stiffnesses are observed for all the specimens in Figure 10. This is because the three horizontal members act as three separate members rather than a single member with a reduced cross section, as observed in Figure 8 and 9 in which curvatures of the three members are significantly different. However, the yield strengths from the tests and the theoretical equations are in good agreement in Figure 10 for all the specimens. The ultimate strengths from the tests and the theoretical equations are considerably similar as well. However, the ultimate displacements from the tests and the equations show unacceptably big errors, which are caused by cumulated strains resulting from the cyclic loadings.

7. CONCULUSIONS

Steel dampers utilizing the flexure-analogy of deformation are proposed. The proposed dampers have the shape of a portal frame composed of one horizontal and two vertical members. Cyclic loading tests were conducted for the four types of the damper specimen, and main findings are summarized as follows. Most specimens fractured with necking in the lower horizontal members. The strengths and deformation capacity of the proposed dampers can be adjusted using the spacing between the horizontal members and the length of the vertical members, respectively. All the specimens meet the requirement proposed by AISC on the cumulative inelastic deformations, while the requirement on the peak deformation capacity is not satisfied by any specimens. Therefore the deformation capacity of the proposed dampers needs to be improved for the application to the actual building structures.

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