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STUDY ON THE HIGHLY DAMPED BUILDING WITH LOW-YIELD-POINT STEEL SHEAR PANEL.

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ABSTRACT

To keep the building safe against earthquake, the energy absorbing element has been developed, which is a type of center pillar utilizing very low yield point (100N/mm^2) steel shear panel damper. This steel shear panel damper is designed to yield in a small deformation range of the frame. This plastic deformation energy can reduces the vibration of the frame.

This paper describes the characteristics of energy absorbing and deformation capacity for the damper, through experiments. The occurrence of buckling of the panel, which is one of the most important criteria for the practical design, could be predicted. The cumulative strain at the first occurrence of buckling is expressed as a simple function of the proposed equivalent width / thickness ratio : $(d/t_w)_{eq}$, regardless the loading hysteresis and types of specimen. And the maximum stress of the damper can also be predicted by the simple function of $(d/t_w)_{eq}$. The hysteresis rule for the damper which reasonably approximates experimental results was introduced. Two parameters for the design of damper installed in buildings are introduced. One is the stiffness parameter and the other one is the strength parameter. The stiffness parameter correlates to the start deformation of energy absorbing, and the strength parameter correlates to the amount of absorbing energy. And their desirable values are proposed by investigating the response of buildings.

KEYWORDS

Vibration control of building; energy absorbing; damper; shear panel; low yield point steel

INTRODUCTION

There are various design concepts to keep buildings safe against earthquakes. The most prevailing one is to design a building to deform uniformly within an acceptable range. (Huang *et al.*, 1994) But, it is still uncertain to predict the actual strength of frame or the behavior after yielding, as various kinds of characteristics of earthquakes are anticipated. In this sense, it is more convenient to divide building into two elements. One support mainly gravitational load, and the other absorb input energy. It is desirable that the structural behavior of energy absorbing elements is clearly understood to take this design strategy.

The Low-Yield-Point (LYP) steel is supposed to be one of the most hopeful among energy absorbing materials. It has a very low yield point (about 100N/mm^2) whereas the Young's modulus is the same as other conventional steels. From this viewpoint, an energy absorbing hysteretic damper, which is a type of center pillar and utilizing LYP steel shear panel at the middle position of it, has been developed (Meng *et al.*, 1995, Miyama *et al.*, 1995). This shear panel is aimed to absorb energy against many cycles of large plastic deformation. The study of the shear panel under these conditions is still rare, because the LYP steel has been recently developed. For he practical design purpose, the design criteria, such as the occurrence of shear buckling, clack, and fracture, should be clarified.

At the design stage of a building installed with this damper, the response characteristics of the building should be investigated, and appropriate strategy to determine the amount of the damper should be established.

LYP STEEL AND LYP STEEL SHEAR PANEL DAMPER

LYP steel has a low yield point as mentioned before and has a small yield / maximum stress ratio around 0.3. Moreover, it has the same value of Young's modulus as that of conventional normal steel. A 1/2 scale LYP panel damper is shown in figure 1. It consisted of two rigid body ends and a LYP steel panel of H-section at the middle position. The flange of it is made of normal steel. The LYP panel was stiffened by ribs in order to increase the buckling load / displacement level of the panel. These ribs could be made of normal or high tension steel. Rigid ends were supposed to be steel column or concrete-encased steel column at the design stage.

Remarkable advantageous features of this damper could be mentioned as follows.
1) This type of damper has less restriction to the space design than the brace or wall type damper.
2) The connection to the frame is simpler than that of other types of damper such as the visco-elastic damper, oil damper, or lead damper. Also, it is maintenance free.
3)The shear panel is welded to flanges by fillet welding which is simple and has enough strength. The ability of deformation can be ensured.
4) The damaged zone is localized in shear panel. The design of other structural members becomes simpler.

MECHANICAL CHARACTERISTICS OF LYP PANEL DAMPER

LOADING TEST

Static shear loading tests were conducted for four series to investigate the mechanical characteristics such as the deformation capacity and hysteretic characteristics. Figure 2 and Table 1 show the shear panels of test specimens. The shear panel was made of LYP steel, and other parts were made of normal steel. And for series B and C, shear panel was connected to the support by high-tension bolts and splice plate.

The tensile test was performed before loading test. Figure 3 shows a relationship between stress and strain of LYP steel. The yield point was defined by 0.2% offset method. The strength increased smoothly and the yield ratio was very small. Table 2 shows the summary of the results of mechanical property of used steels.

One of the most important parameters of this type of damper is the equivalent width/thickness ratio$(d/t_w)_{eq}$, which is the index for the elastic shear panel buckling. In this study, it is used as the index for mechanical characteristics of the damper in the plastic range such as the energy absorbing capacity, deformation capacity, maximum shear stress, etc. The $(d/t_w)_{eq}$ is easily determined from the size for the type a and b with square shape and no rib using the aspect ratio. But for the rectangular shear panel with ribs, the $(d/t_w)_{eq}$ is defined as follows. The buckling load of supposed square panel with $(d/t_w)_{eq}$ gives the same buckling strength of actual rectangular shear panel with flange and ribs. And the buckling load of the shear panel is calculated by appropriate numerical method. In the table 1, $(d/t_w)_{eq}$ are shown which was set at the range of around 20 to 80. Type d, e and f, stiffened by ribs to decrease $(d/t_w)_{eq}$,were intended to practical use. An example of loading apparatus is shown in Figure 4 for series B. Cyclic shear displacement was imposed at the upper end of the specimen, under the condition that any flexural moment was not generated at the position of the center panel.

The imposed cyclic displacement schemes are conceptually shown in figure 5. For series A and B, the amplitude was increased every cycle, in order to investigate the basic characteristics of LYP steel shear panel. For series C, the amplitude increases every 3 cycles. And for series D, the cyclic loading was applied in a same amplitude which was assumed to the maximum deformation in the practical design, until the buckling of the panel became obvious. After the occurrence of buckling, the amplitude was magnified.

EXPERIMENTAL RESULTS

Table 3 shows the summary of the results. The definition of buckling occurrence will be mentioned later.

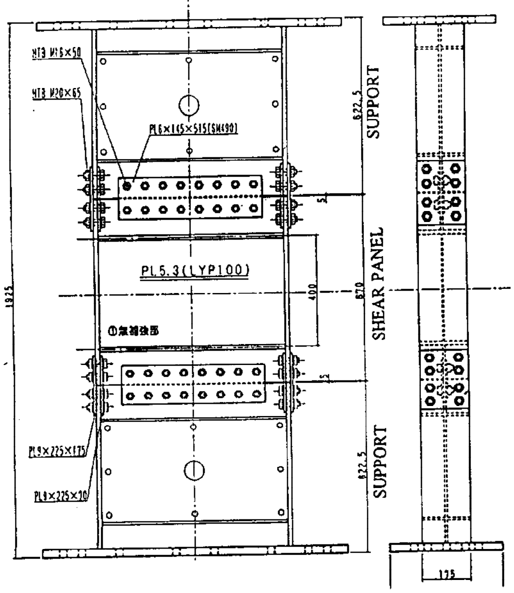


Fig. 1. 1/2 Scale LYP Shear Panel Damper

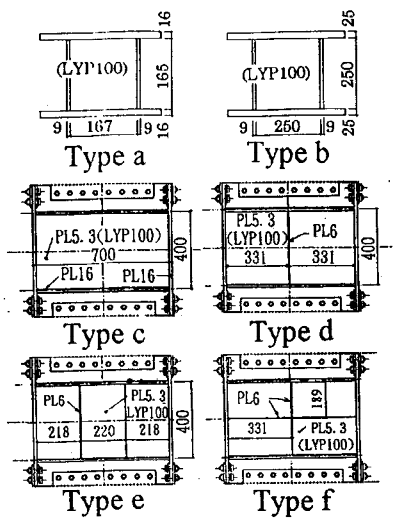


Fig. 2. Shear Panels of the Specimen

Table 1. List of Specimen

NAME	Type	t_w mm	$(d/t_w)_{eq}$
Series A			
LA20	a	8.6	19.4
LA30	a	5.4	30.9
Series B			
LB40	b	6.0	41.7
LB50	b	4.9	51.0
LB60	b	4.0	62.5
Series C			
No. 1	c	5.3	77.5
No. 2	d	5.3	57.4
No. 3	e	5.3	43.6
No. 4	f	5.3	38.8
Series D			
No. 11	f	6.0	33.7
No. 12	f	6.0	33.7

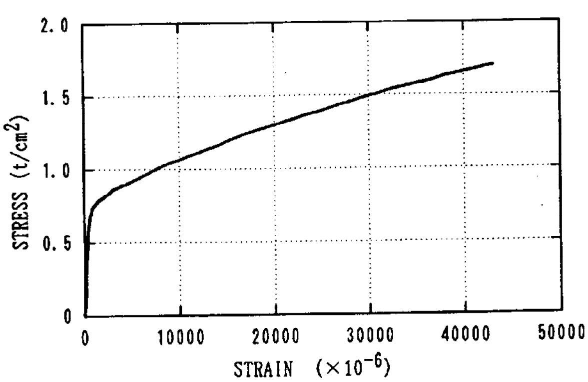


Fig. 3. Results of Tensile Test (LYP)

Table 2. Summary of Tensile Test

Element	thickness mm	yield point t/cm^2	tensile strength t/cm^2	elongation %
Rib	5.7	3.71	5.46	24.1
Flange	8.6	3.85	5.46	24.5
Flange	15.6	3.41	5.36	26.3
Panel	5.1	0.77	2.36	63.5

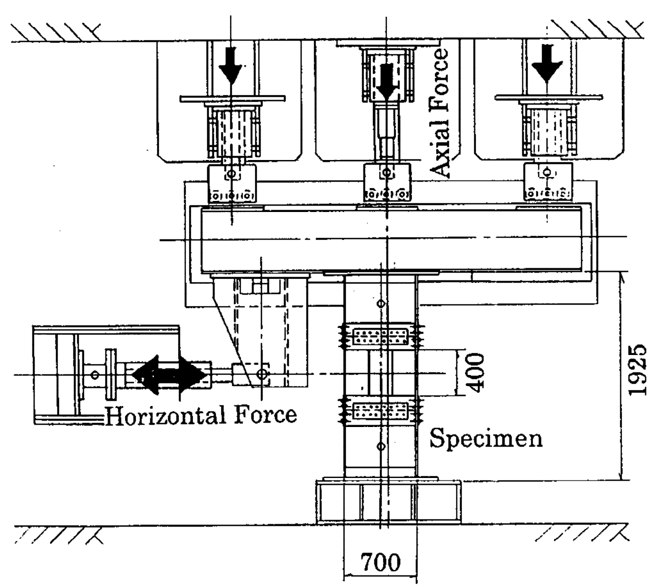


Fig. 4. Loading Equipment

Figure 6 (a) to (d) show examples of relationship between shear stress and shear deformation angle of the panel as the results of loading test, whose $(d/t_w)_{eq}$ is different as shown in table 1. For the case of No. 1 (Figure 6 (a)), the shear stress increased as the displacement amplitude increased until the first cycle of the shear strain amplitude became 1.5×10^{-2}. At the second cycle of this strain range, the plastic shear buckling appeared and the hysteresis loop showed the concave features. This concavity was defines as the shear panel buckling in this study. The configuration of those results was strong dependent of the value of $(d/t_w)_{eq}$. For the case of No. 4 (Figure 6 (c)), which had small $(d/t_w)_{eq}$, the loop shape is fatty and round, and the shear stress of each loop increased as the displacement amplitude increased, until shear strain amplitude became 3.5×10^{-2}. After this range, the panel buckling and the concave features of the hysteresis loop appeared. The amplitude range of this specimen is larger than that of No. 1 specimen with larger value of $(d/t_w)_{eq}$. In case of LA30, which is shown in Figure 6 (d), the panel buckling did not appear during the cyclic loading. The shear stress of each loop increased as the amplitude range increased. At the last loading stage of this specimen, a crack appeared at the welded zone of the fillet. These results are summarized as follows. The displacement amplitude, where the shear panel buckling and concave feature occurred, increased as the $(d/t_w)_{eq}$ decreased. And the panel buckling did not occur as long as $(d/t_w)_{eq}$ is less than 31.0.

The occurrence of the buckling and the concave feature of the hysteresis loop is one of the deterioration criteria for the shear panel. This criteria is related to the cumulative shear strain. The cumulative strain is shown schematically in Figure 7. The half positive/negative side of the hysteresis loops is put on the strain axis cumulatively.

Figure 8 presents the relationship between cumulative strain at the first occurrence of buckling and $(d/t_w)_{eq}$ of the LYP panel. The buckling and the concave feature did not appear for the specimen LA20 and LA30 whose $(d/t_w)_{eq}$ are less than 31.0. The plotted points are reduced to a simple curve. Even though the shapes of those specimens were different by series, and those specimens were different in the cyclic loading pattern. This single curve could be expressed by Equation (1).

$$r=1.36\times10^{4}(d/t_w)_{eq}^{-2.67} \tag{1}$$

r: cumulative shear strain at the first occurrence of buckling

This empirically obtained equation is one of the most important design criteria of the damper.

The relationship between the maximum cumulative shear strain and the $(d/t_w)_{eq}$ is shown in Figure 9. The cyclic loading was stopped before the appearance of the concave feature for series A and series C. It could be said

Table 3. Summary of Experimental Results

Name	$(d/t_w)_{eq}$	occurence of buckling	maximum value		
		cumulative strain	cumulative strain	maximum strain	maximum stress
	d/t_w	%	%	%	t/cm²
Series A					
LA20	19.5	—	157.3	20.20	2.682
LA30	31.0	—	142.5	20.00	3.023
Series B					
LB40	41.2	67.9	121.0	15.46	1.915
LB50	50.2	27.1	90.9	13.78	1.591
LB60	62.2	18.6	87.0	10.01	1.595
Series C					
No. 1	77.5	10.0	148.8	6.95	1.186
No. 2	57.5	18.7	157.3	6.43	1.328
No. 3	43.6	48.4	152.5	6.95	1.486
No. 4	38.8	80.2	153.0	7.40	1.683
Series D					
No. 11	33.7	79.3	205.3	11.56	1.990
No. 12	33.7	85.7	214.7	11.29	1.951

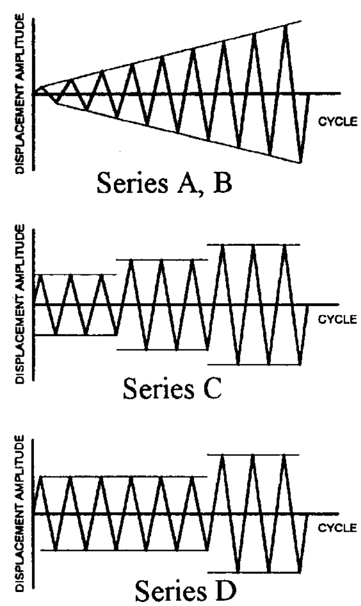
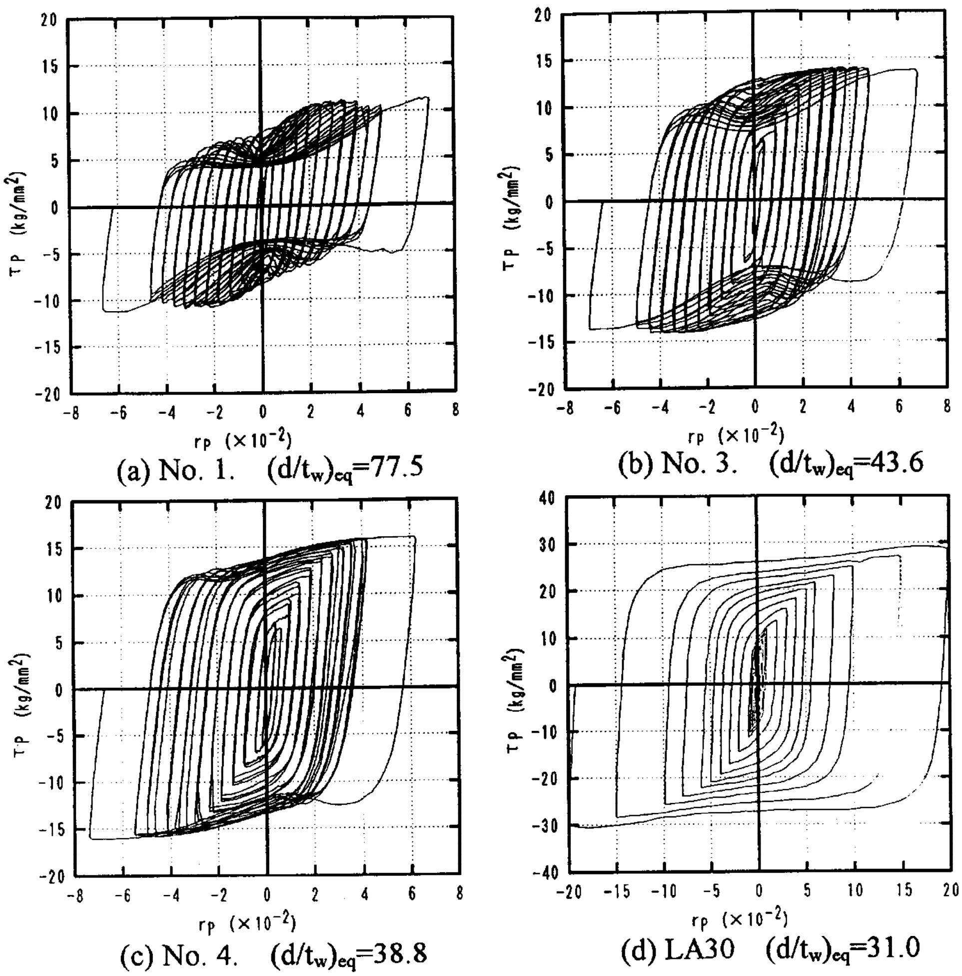


Fig. 5. Loading Pattern

that the deformation capacity of those specimens might be underestimated. For series B, the crack occurred on panel in a smaller cumulative strain than that for series C, because those specimens are tested in a larger strain amplitude range. There are small difference in deformation capacity and the understandable reasons could be considered above. But the maximum cumulative shear strain of the specimens were almost same value, in spite of the difference of $(d/t_w)_{eq}$. And the maximum cumulative shear strains were still more than 1.



(a) No. 1. $(d/t_w)_{eq}$=77.5

(b) No. 3. $(d/t_w)_{eq}$=43.6

(c) No. 4. $(d/t_w)_{eq}$=38.8

(d) LA30 $(d/t_w)_{eq}$=31.0

Fig. 6. Typical Example of Hysteresis Loops

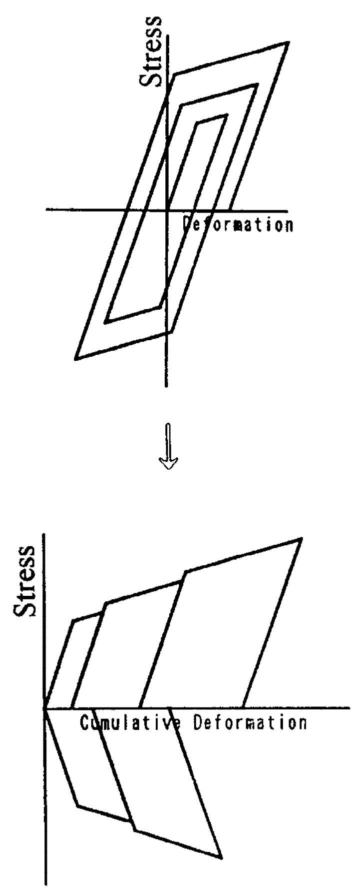


Fig. 7. Cumulative Strain

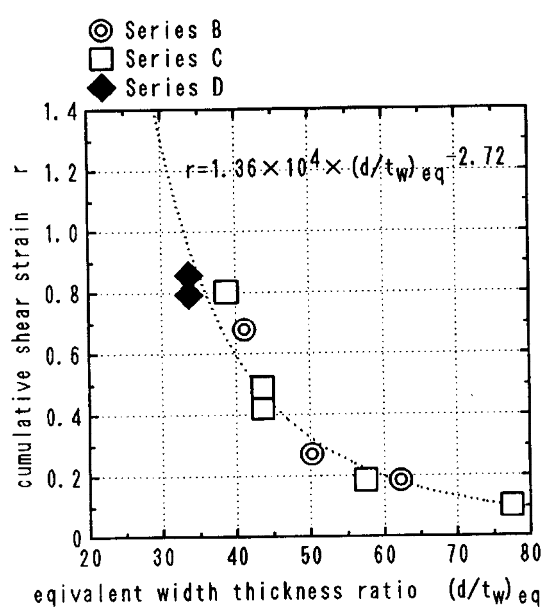


Fig. 8. Cumulative Shear Strain when Concave Feature Appears

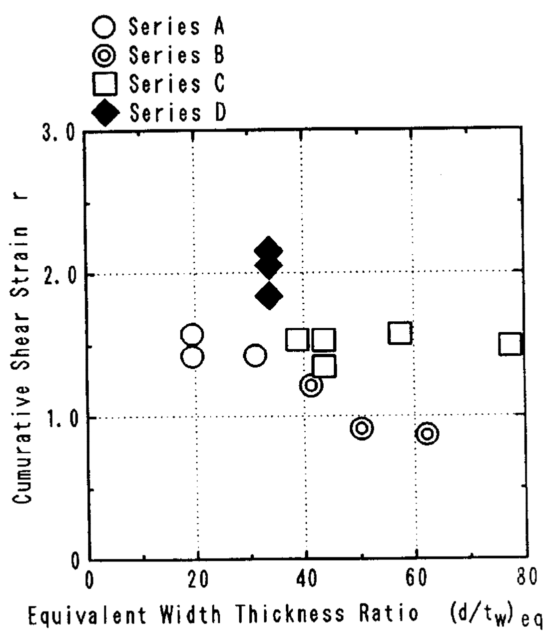


Fig. 9. Cumulative Shear Strain at the Last Stage

The relationship between the maximum shear stress and the $(d/t_w)_{eq}$ is shown in Figure 10. The maximum shear stress decreased as the $(d/t_w)_{eq}$ increased in the same manner of the relationship between the cumulative shear strain and the $(d/t_w)_{eq}$. Because the buckling and concave feature occurred in a small strain range for the specimen which had larger $(d/t_w)_{eq}$ value. The maximum shear stress of series C is smaller than that of series A and B. The difference of strain amplitude might cause these results or there might be some unknown factors influenced to the maximum shear stress. But from this figure, these results were reduced to a simple curve as the function of $(d/t_w)_{eq}$. This single curve could be expressed by Equation 2.

$$\tau = 22.93(d/t_w)_{eq}^{-0.689} \ (t/cm^2) \tag{2}$$

τ: maximum shear stress

HYSTERESIS MODEL OF THE LYP PANEL DAMPER

The hysteretic characteristics of the LYP shear panel damper are 1) increasing the shear force with repeated loading, 2) having more round fatty loop at the Bouschinger's effects zone. In this study, Meng-Ohi-Takanasi model (Meng *et al.*, 1992) is used as the hysteresis model. The Bounschinger's effects can be expressed by the

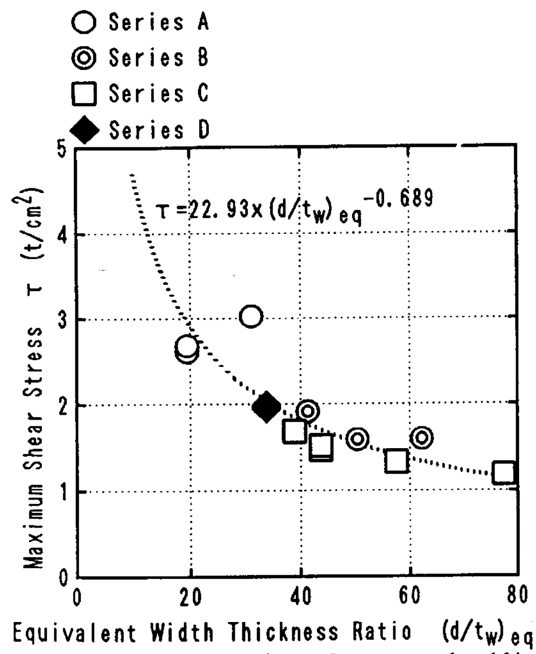


Fig. 10. Maximum Shear Stress to the $(d/t_w)_{eq}$

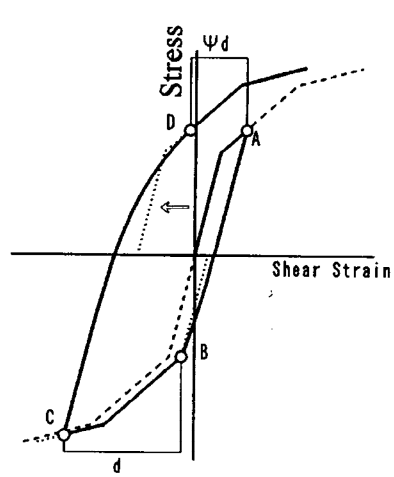


Fig. 11. Hysteresis Model

$\alpha = Q_d/Q_f$

$\kappa = K_d/K_f$

Q_d: Yield Strength of the Damper

Q_f: Design Shear Strength of the Structure

K_d: Stiffness of the Damper

K_f: Stiffness of the Frame

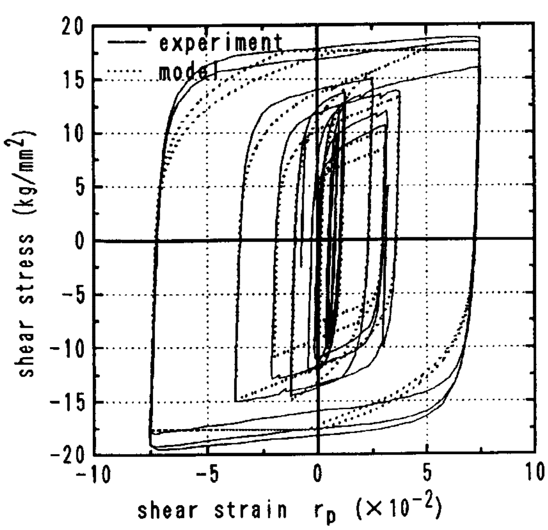


Fig. 12. Hysteresis Loops of Experiment and Model

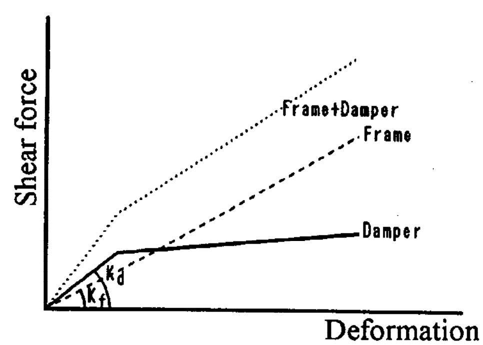


Fig. 13. Non-dimensional Parameter α and κ

function derived from Ramberg-Osgood model for the curve shape. And the increment of the shear stress can be expressed by shifting the target point on the tri-linear skeleton curve.

This model is shown in Figure 11 schematically. The plastic deformation in negative stress range is d (from point B : old target point to the point C : unloading point). The skeleton curve is shifted through the distance Ψ d and the target point D is the same stress point of previous unloading point A on the skeleton curve. Ramberg-Osgood function is applied from point C to D. And when the shear stress excess point D, the shifted skeleton curve is used as the new loading curve. If unloading occurs on the curve C to D, which is on the Ramberg-Osgood function, Ramberg-Osgood model is used as the inner loop. Figure 12 shows the shear-force deformation loops, to check the agreement of adopted model and experimental results. It is shown that this model can express the LYP steel damper well.

THE RESPONSE CHARACTERISTICS OF THE BUILDING INSTALLED LYP DAMPER

At the design stage of a building installed of the damper, it is very important to determine the amount of damper. Two parameters are applied to install this damper. They are strength parameter α and stiffness parameter κ. They are shown schematically in Figure 13. The shear strength of the damper is defined as αQ_f, where Q_f is the design shear force of the building, that aimed all the damper to yield at the same time in a small deformation level. It is desirable that the distribution of the total stiffness along the stories is smooth.

The numerical parametoric analysis were performed using the 22-story building to obtain the design information of the damper. This was a imaginary office building. The parameter α and k is set to be constant in all stories of the building for each case. The shear and bending stiffness of each story are obtained by static analysis of the building. The stiffness proportional damping was applied, and its ratio was set to be 2% for 1st mode of the building without damper. The input earthquake motions are El Centro NS 1940 and Hachinohe EW 1968, and the maximum velocity of them are magnified to be 50 cm/sec.

Figure 14 and Figure 15 show the maximum story drift angle for κ=1.0 and κ=2.0 respectively. The story drift angle decreases as α increases, because larger α make larger hysteresis loop and absorb much energy. And the story drifts out of middle stories are reduced extremely and the distribution of story drift become smooth.

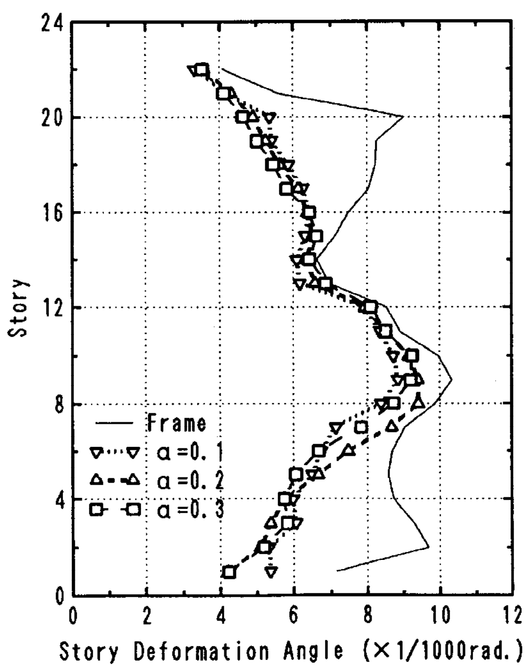


Fig. 14. Maximum Story Drift Angle (κ=1.0)

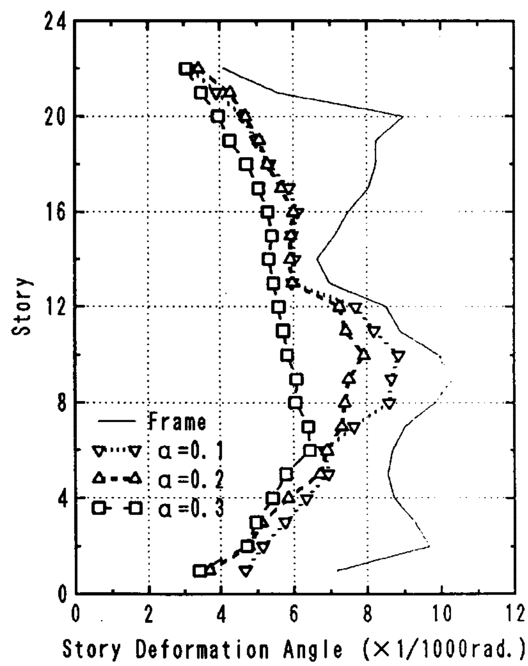


Fig. 15. Maximum Story Drift Angle (κ=2.0)

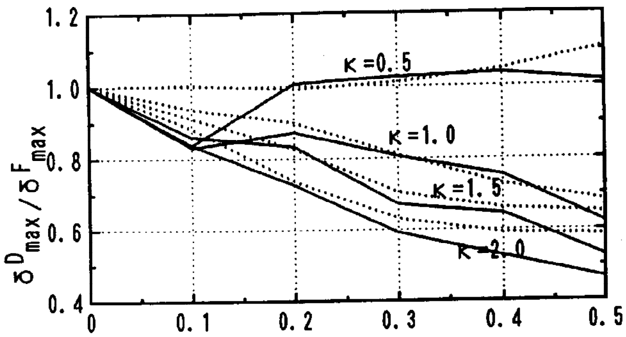


Fig. 16. Maximum Story Drift ft

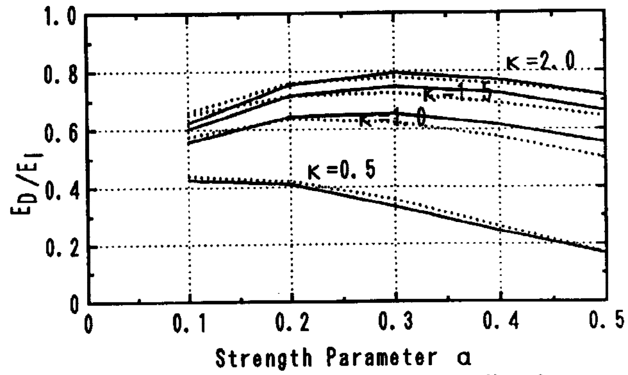


Fig. 17. Dissipated Energy Normalized by Input Energy

To investigate the effect of α and κ on the story drift, Figure 16 shows the reduction of the maximum story drift (δ^d_{max}) normalized by that of the building with damper (δ^f_{max}). In case of κ=0.5, the story drift does not always decrease, but it decreases in case of $\kappa \geqq 1.0$. Also the story drift decreases as α increases for both earthquakes. The ratio of absorbed energy of the damper (E_D) normalized by the input energy (E_I) is shown in Figure 17. In the case of κ=0.5 and α=0.1, more than 40% of input energy is absorbed by the damper. And in case of $\kappa \geqq 1.0$, more energy is absorbed, and the ratio tends to have a peak when the value of α is from 0.2 to 0.3. Judging from these results, $\kappa \geqq 1.0$ and $\alpha \geqq 0.1$ values could be essential condition for the effective use of the damper. Especially, α=0.2 to 0.3 is desirable.

CONCLUDING REMARKS

The characteristics of LYP panel damper of center pillar type was discussed through experiments. And the effects of the damper was investigated by response analysis.
Major findings could be summarized as follows.
1) This damper has a sufficient energy-absorbing capacity even after the occurrence of buckling of panel.
2) The design criteria for the first occurrence of buckling is expressed as a simple function of accumulated displacement and $(d/t_w)_{eq}$.
3) The maximum cumulative shear strain is more than 1.
4) The maximum shear stress is expressed as a simple empirical expression using $(d/t_w)_{eq}$.
5) The hysteresis model is proposed which agrees well with the experiment results.
6) The design parameters of the damper installed in buildings are proposed, and the desirable value of them are also shown.

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