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EXPERIMENTAL STUDY ON DAMAGE FREE STEEL FRAME INCORPORATING WITH LEAD DAMPER INTO BEAM SPLICE

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SUMMARY

In order to establish methodology to construct damage free steel structure, this paper presents a method of incorporation of proposed lead damper into the beam splice, and result of verification test performed using full scale beam-column subassemblage. The subassemblage was subjected to sinusoidal and random excitations, by controlling the tip deflection of the beam. The result has shown that the lead damper can behave effectively as energy absorbing device, regardless of variety of input frequency, and cannot deteriorate under considerable number of repetitive cyclic loadings. Thus, the usability of proposed method can be verified fairly well.

INTRODUCTION

In the present seismic design of steel structure in Japan、the design concept is generally recognized so that for the severe earthquake which is expected to very rarely occur, members of the structure would sustain its plastic deformations within the extent to prevent collapse, and that for small and moderate earthquakes, the buildings would behave within their elastic ranges, so as to keep original function.
However, there is no guarantee where the structure does not collapse against subsequent severe earthquakes, even if the members are guaranteed the security of structural safety for severe earthquake in the first time. Therefore, it becomes important to judge whether any strengthening, repair or reconstruction is necessary or not, after the structure has experienced the destructive earthquake. And post earthquake redundancy of the structure must be grasped according to the degree of the damage. However, it is very difficult to accurately grasp redundancy of the structure after the severe earthquake. For example, it is not easy to estimate the redundancy until rupture of the beam-column welded joints after the joints experienced the complex strain histories, because the joint performance greatly fluctuates by the difference between not only quality of used material but also condition of welding process.

For this reason, it will be recommended to apply a method in which the structure remains within its elastic range during severe earthquakes, so as to make the structure damage free, for solving the contradiction of the current aseismic design method. Although seismic isolation system and the structure incorporated with several kinds of damping devices have been already proposed and utilized, there are many problems to

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solve from the viewpoints of ease of maintenance, economy and space saving in installing such devices. In order to save the space for installation and cost, several methods are proposed in the manner of installing the energy absorption devices into column, beam and the connection, as reported in Popov et al [1] and Butterworth [2].

The authors [3] have already started the fundamental research on the mechanical property of lead damper using a prototype specimen, and have confirmed the fundamental performance necessary to obtain a goal of incorporated with the proposed damper into the beam splice in steel moment resisting frame. After additional research has been carried out to realize the method, it has been cleared that some improvement has been necessitated on the inner detail of the damper.

This paper deals with an outline and the results of static and dynamic experiments using full scale beam-column subassemblage incorporating with newly developed lead damper, to verify the performance of the damper.

EXPERIMENTAL PROCEDURE

Geometry and mechanism of lead damper

The damper used for the experiment has the shape of the rectangular prism 460 mm long, 120 mm wide and 180 mm high, as shown in Fig. 1. The damper is composed of several parts, like as slider, orifices and lead blocks, as shown in the sectional view of Fig. 2. When the slider push the upper and the lower lead blocks framed between the slider and metal block, plastic flow of lead will occur at or near the orifices, and the damper generates resisting force, as already reported by Skinner et al [4]. Furthermore, in this damper, there are total 4 orifices, so as to uplift the resisting force due to lead extrusion, as in Fig. 2.

Two circular rods protruding from the slider are connected with rectangular shaped rods, in order to transfer the resisting force to the structural components like as beams of steel frame.

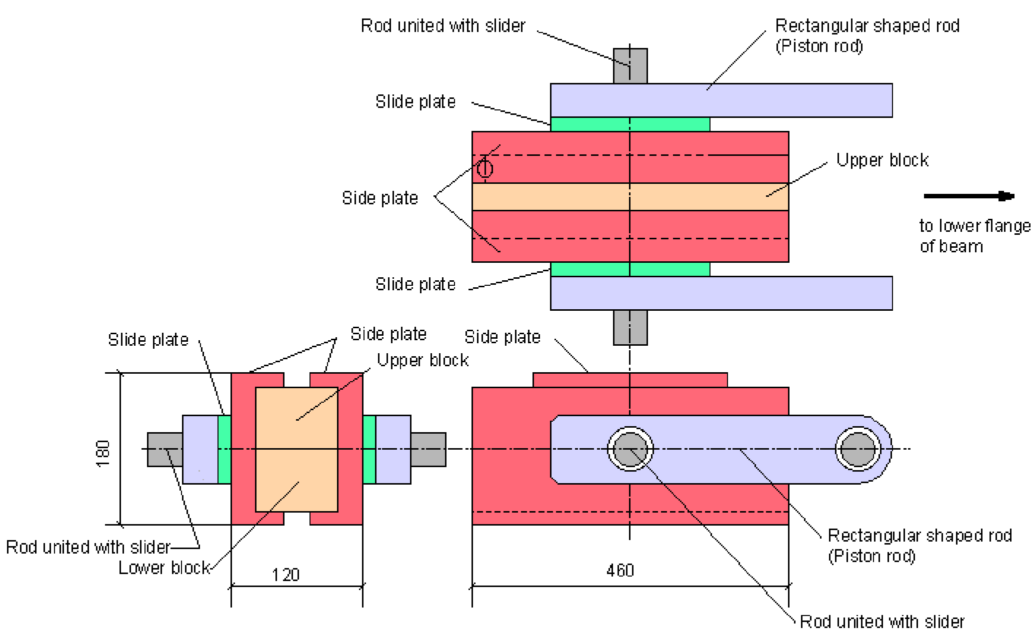


Fig. 1 Outer View of Lead Damper (unit: mm)

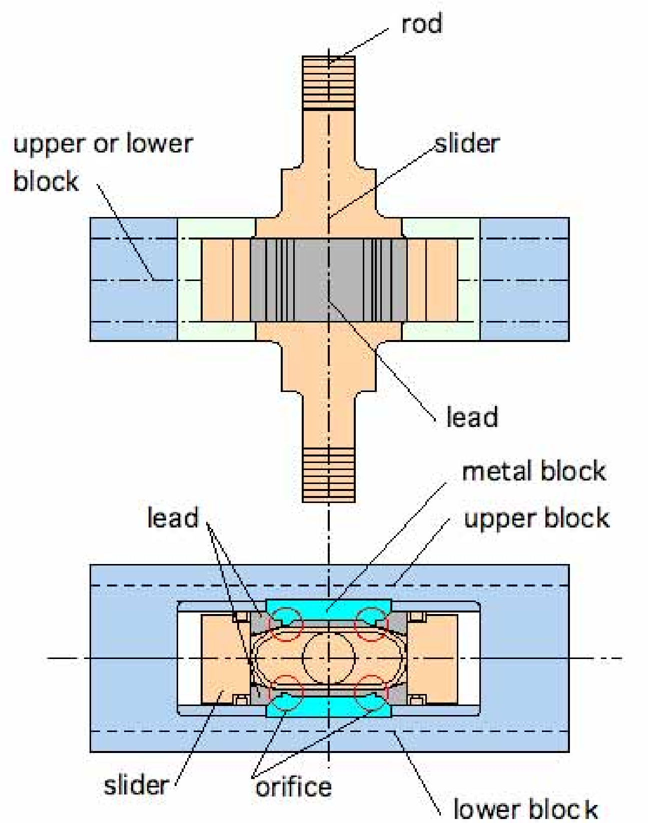


Fig.2 Cross Section of Lead Damper

Beam-column subassemblage incorporating with lead damper

When deciding the method how to incorporate with the damper into the beam splice, special attention should be paid as follows. First, it should be taken into consideration the suitable position of incorporation of the damper into the splice. It may be desirable that center of rotation of the beam at the splice is made to be the upper flange side, since the floor system in the ordinary steel building is placed right above the upper flange of the beam. Otherwise, the damper would not behave freely due to restriction of the floor system, provided that the special consideration would be taken for rotation mechanism of the floor system, in case of incorporating the damper into the upper flange side. For this reason, the upper flange of the beam is pin jointed to the gusset plate connected with the column, so as to rotate freely about the axis through the center of the upper flange plate.

The second attention concerns in the maximum stroke of the damper. Since it is generally recommended that the maximum inter-story drift angle comes to about 0.01 in the event of severe earthquake, the maximum deflection amplitude of the damper can be estimated as 0.01 times the beam depth. This means that the stroke of the damper yields to 4 to 8 ㎜, when the beam depth is 400 to 800 ㎜, and that the damper has to resist effectively from the comparatively small deflection amplitude.

Detail of the beam splice is designed so as to satisfy the aforementioned conditions, as shown in Fig. 3. A newly developed clevis at the upper flange splice of the beam and a connecting device at the lower flange splice to fasten the lower beam flange to the damper, were fabricated and assembled so as to shape the full scale beam-column subassemblage. Built-up wide flange sectioned column (BH- 400x400x25x25) and rolled wide sectioned beam (H-500x200x16x22) were used to shape the subassemblage, and they were made of JIS SM490B. Fig.4 illustrates the test set-up. Each end of the column was pin-connected to the rigid frame, which was fixed to the concrete test bed. A hydraulic actuator and the beam were pin jointed together at the tip of the beam to apply the load. Lateral guides were arranged at the points where the beam length was divided into three equal parts, so as to prevent lateral buckling of the beam. Since the beam end was not being rigidly joined to the column flange, shear force of the beam can be transferred directly to the column through the clevis at the upper beam flange. Then, it becomes that the damper is subjected to the axial force alone, which can be approximately estimated by dividing bending moment at the beam end by the depth of the beam.

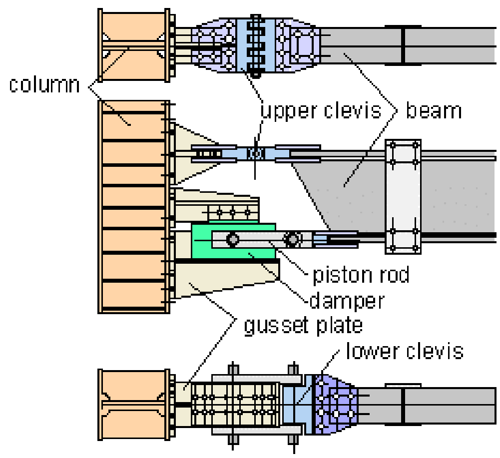


Fig.3 Detail of Beam Splice

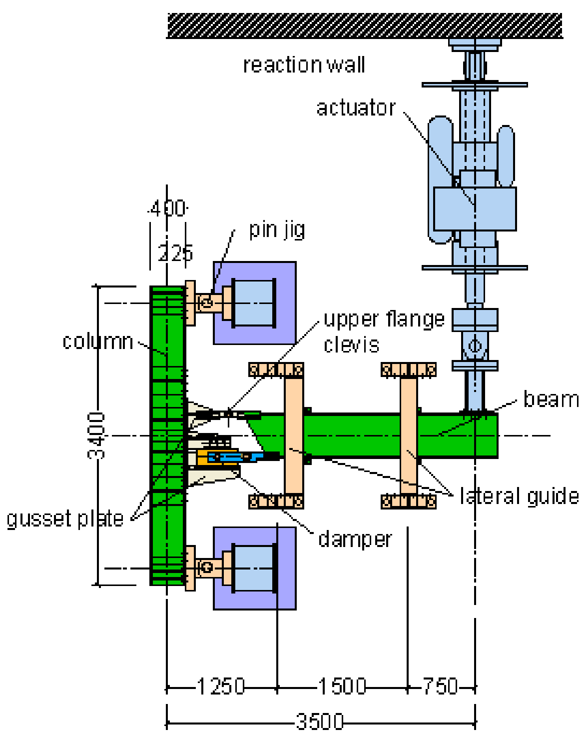


Fig.4 Test Set-up (unit: mm)

Test specimen type

Materials of lead used for the experiment are classified into two types, according to the difference of chemical composition. One is so called pure lead with lead content of 99.99%, and another is lead alloy with antimony content of 1.93%. In this paper, the damper using the former material is called as PL-type, and the damper of the latter is named as SL-type. PL-type damper is composed of PL1 and PL2 specimens using identical material.

Measurement

During the experiment, essential measures were made about applied load, overall and local displacements, local strains and temperature of the outside of the damper. In this paper, P denotes the applied force and the deflection at the beam tip is shown by the symbol, Δ. For resisting force and deformation of the damper, the symbols Pd and δ are used respectively. δ is the displacement of the slider in the damper, which was detected by a pair of laser sensor. In order to evaluate Pd from the outputs of strains pasted on the rectangular rods, the calibrated relation between load and strain was applied, based on the result of static loading test by using identical lead damper unit, which had been conducted prior to the subassemblage test.

Loading condition

In the experiment, the subassemblage was loaded in the manner of applying the forced tip deflection to the beam, with several excitation frequencies and loading patterns, and the test was conducted under static and dynamic loading conditions. In the static loading conducted only at the initial stage for each test, the tip deflection was set incrementally at the range from 0 to plus minus 40 mm, under cyclic reversed loading condition. The dynamic loading test was carried out soon after the static loading test, and it was composed of sinusoidal and random excitation tests. The sinusoidal excitation test was conducted at constant tip deflection amplitudes with three step frequencies of 0.5Hz, 1.5Hz and 2.5Hz in order, except the case of deflection amplitude of 50 mm, and the number of repetitive loading cycles was 10 for each frequency range. The constant tip deflection amplitudes were set at three steps of 20, 40 and 50 mm in incremental loading path. After finishing the excitation test at the deflection amplitude of 50 mm, the sequence of loading was made to be in decrement. That is, overall loading history in the sinusoidal excitation test was 20 - 40 - 50 - 40 - 20 mm in deflection amplitude. The excitation test of 50 mm deflection amplitude at the frequency 2.5Hz couldn’t be made, because the loading speed was beyond the servo actuator’s capacity.

In the random excitation test, the forced tip deflection was evaluated from the result of dynamic analysis of model structure subjected to earthquake excitation, as follows. The deflection-time relation was created by translating time history of beam rotation angle in typical 3story and 3 bay moment resisting steel frame subjected to actual seismic acceleration of El Centro 1941 NS component or JMA Kobe 1995 NS component with the duration of 10 sec., to the time history of the beam tip deflection of the test subassemblage. The program developed by Ogawa and Tada [5] was used for dynamic analysis of the model frame.

The loading history for each damper specimen was different, since objective of the experiment was focused on effects of excitation frequency, the number of loading cycles, and randomness of deflection, in order to verify usability of the structural system incorporating with proposed lead damper. An example of loading history (loading path) is tabulated in Table 1. In the table, the name of the loading path in the sinusoidal excitation test is distinguished from each other by numbering as 1 or 2, in accordance with the ascending or descending path in deflection amplitude. The random excitation tests in Table 1 are classified by the values of tip deflection amplitude, strength ratio, duration of time and magnification factor. Since the dynamic analysis had been performed by setting the resisting force of virtually assumed damper to 0.2 to 0.6 times the yield force of the joining beam flange, the strength ratio of beam to assumed damper in the analysis is denoted here by strength ratio. The maximum tip deflection obtained from the analytical result as mentioned above was initially scaled to 40 mm. And the input time history of the tip deflection of 20 mm at the maximum was created by multiplying El-40 data by 0.5. Since the duration in the input excitation was originally equal to 10 sec, and the duration of the loading path with the original duration is expressed as 1.0 in Table 1. For the loading path of the duration of 2.0, the time was enlarged as much as 20 sec. This is the case of PL1 specimen, and also the loading history of SL specimen is almost same. The history of SL specimen is different from those of PL type specimens. For SL specimen, after static loading at the initial stage, the random excitation test was carried out, using tip deflection time history derived from the result of dynamic analysis under the ground acceleration of JMA Kobe 1995 NS component, prior to the sequential sinusoidal excitation test.

Table 1 Loading Condition of PL1

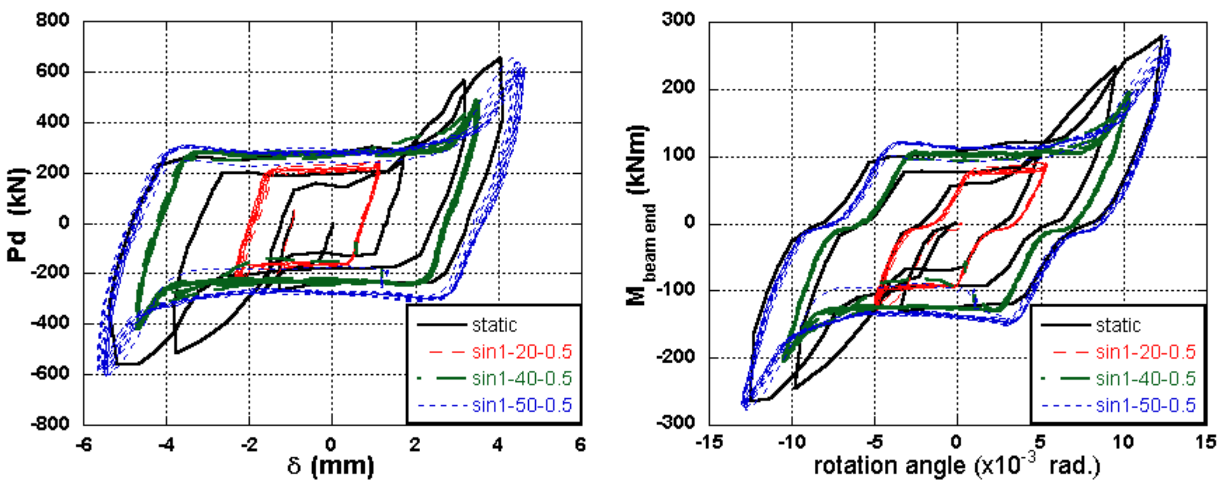
	loading name	freq. (Hz)	disp.amp. (mm)	cycle	strength ratio	duration	magnification factor
1	static	-	50	-	-	-	-
2	sin1-20-0.5	0.5	20	10	-	-	-
3	sin1-20-1.5	1.5	20	10	-	-	-
4	sin1-20-2.5	2.5	20	10	-	-	-
5	sin1-40-0.5	0.5	40	10	-	-	-
6	sin1-40-1.5	1.5	40	10	-	-	-
7	sin1-40-2.5	2.5	40	10	-	-	-
8	sin1-50-0.5	0.5	50	10	-	-	-
9	sin1-50-1.5	1.5	50	10	-	-	-
10	sin2-40-0.5	0.5	40	10	-	-	-
11	sin2-40-1.5	1.5	40	10	-	-	-
12	sin2-40-2.5	2.5	40	10	-	-	-
13	sin2-20-0.5	0.5	20	10	-	-	-
14	sin2-20-1.5	1.5	20	10	-	-	-
15	sin2-20-2.5	2.5	20	10	-	-	-
16	sin3-20-0.5	0.5	20	10	-	-	-
17	El-20-0.2	-	20	-	0.2	1.0	0.5
18	El-40-0.2	-	40	-	0.2	1.0	1.0
19	El-20-0.4	-	20	-	0.4	1.0	0.5
20	El-40-0.4	-	40	-	0.4	1.0	1.0
21	El-20-0.6	-	20	-	0.6	1.0	0.5
22	El-40-0.6	-	40	-	0.6	1.0	1.0
23	El-20-0.6-2	-	20	-	0.6	2.0	0.5
24	El-40-0.6-2	-	40	-	0.6	2.0	1.0

EXPERIMENTAL RESULT

Result of sinusoidal excitation test

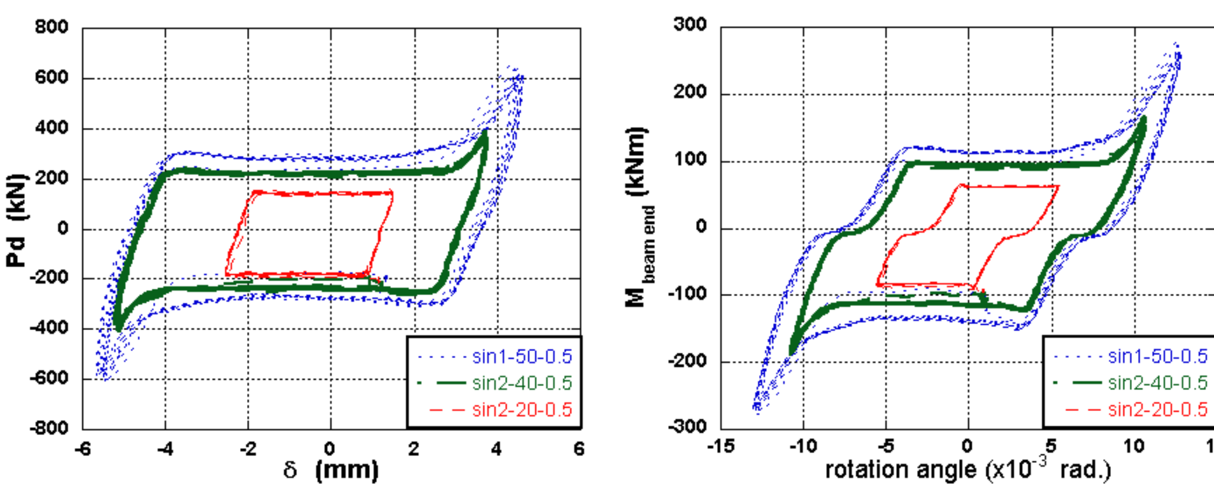
The response characteristics of the lead damper are summarized on the load-deflection relationship. Hereafter, the resisting force Pd-relative displacement δ relation of the damper will be referred simply as load-deformation relation of damper. The applied load P-tip deflection Δ relation is transferred to the moment at the beam end-rotation angle relation, in order to evaluate directly the contribution of the damper on both strength and deflection. The rotation angle of the beam is calculated, after subtracting the elastic deformation components due to panel, column and beam distortions from the original tip deflection of the beam, Δ.

The examples of these relations are shown in Fig. 5 to 8. In the figures, Figures (b) show the moment-rotation relation, so as to correspond to Figures (a), which illustrate the load-deformation relation of damper, for every loading path. The load-deformation relation of damper in Fig. 5 (a) illustrates the results of experiment, from static loading to sinusoidal excitations at the tip deflection amplitudes of 20 to 50 mm in ascending loading path under the constant frequency of 0.5 Hz. From the figure, it can be recognized that the hysteresis loop has the shape of parallelogram within the region of comparatively small deflection amplitude, or slip type with steep increase of the resisting force near the reversed point, so called as pinching, though the skeleton curve is like as round house form. In descending loading path, namely, the path of tip deflection amplitude from 50 to 20 mm, the hysteresis loop shapes are almost similar with those in the incremental path, as shown in Fig. 6 (a). The characteristics of moment-rotation relation, as shown in (b) of Figs. 5 and 6, are also similar to those of corresponding load-deformation relation of damper, as described above.



(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

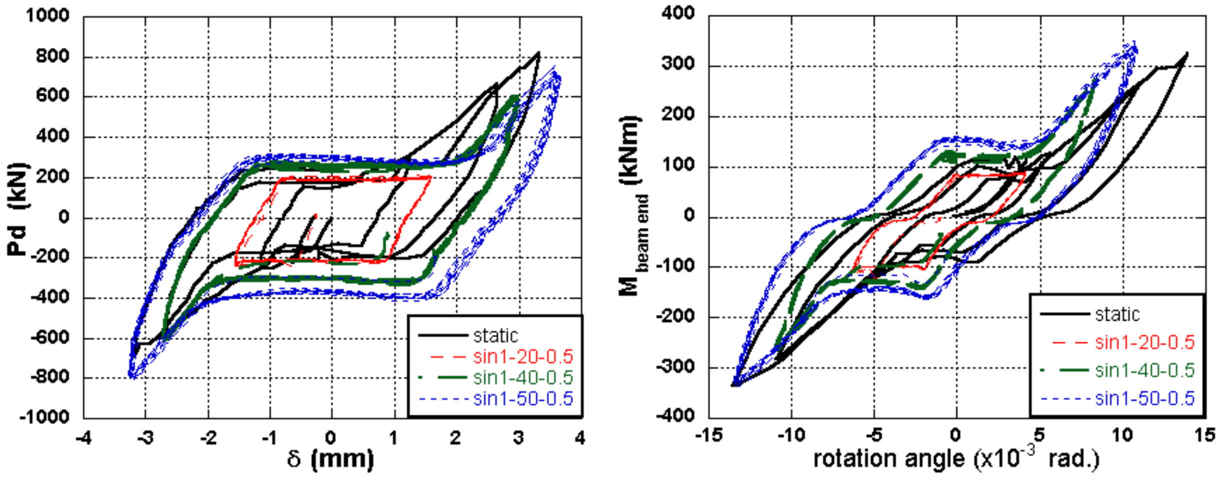
Fig. 5 Experimental Result of PL1 Specimen in Ascending Loading Path



(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

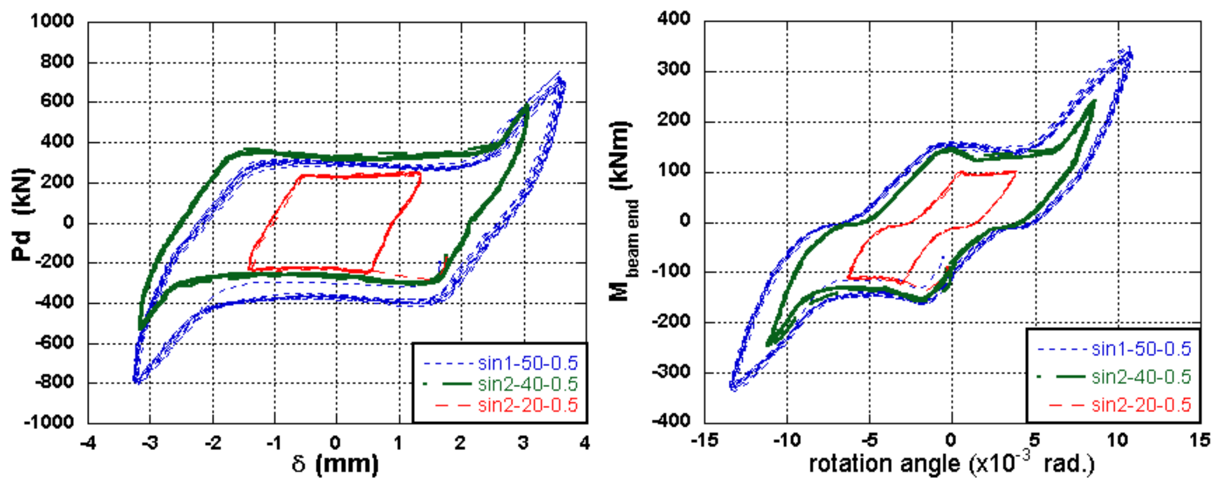
Fig. 6 Experimental Result of PL1 Specimen in Descending Loading Path

The experimental results of SL specimen are shown in Figs. 7 and 8. The figures show the results in the ascending and the descending loading paths, respectively. The results are somewhat different from those of PL specimen, though the shape of hysteresis loop resembles each other. That is, the resisting force in SL specimen is comparatively high in comparison with the value of PL1 specimen. At the same time, pinching effect can be observed more remarkably, in SL specimen.



(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

Fig. 7 Experimental Result of SL Specimen in Ascending Loading Path

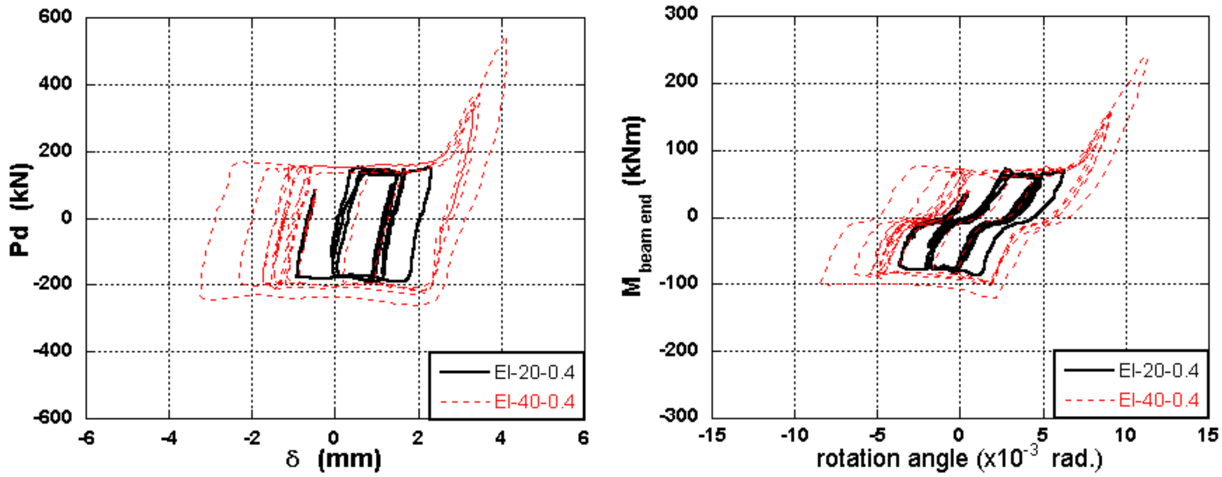


(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

Fig. 8 Experimental Result of SL Specimen in Descending Loading Path

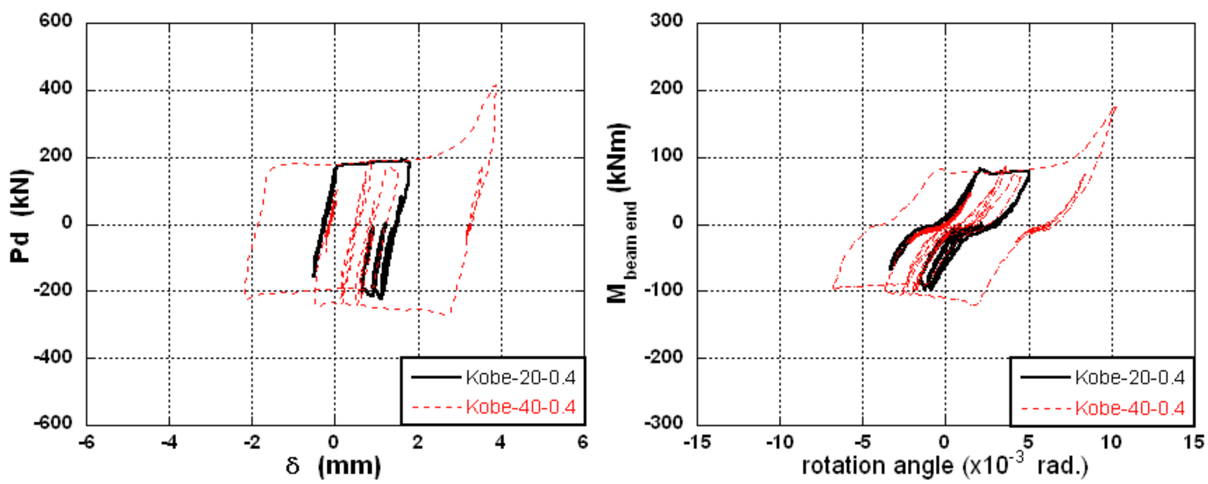
Result of random excitation test

The examples of hysteretic behavior under random excitations are illustrated in Figs. 9 and 10. Fig. 9 shows the results of PL 1 specimen under the excitations simulated the response of El Centro earthquake, and Fig. 10 shows the result of PL 2 under Kobe earthquake. From Fig. 9, it can be recognized that the hysteresis loop shapes are stable, even after the damper was subjected to cyclic repeated loadings over 140 cycles. However, special attention should be paid to the appearance of steep pinching at the displacement reversal point, and further improvement of the damper against pinching will be necessary in order to stabilize the dynamic response of the structure. Since PL 2 specimen experienced the excitation of the simulated Kobe earthquake after static loading and was subjected to the sinusoidal excitations subsequently, the loading history is different from the case of PL 1. The hysteresis loops of PL1 and PL 2 are stable under random excitations, regardless of the amount of loading cycles.



(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

Fig. 9 Experimental Result of PL1 Specimen under Random Excitations (El-20, 40-0.4)



(a) Pd-δ Relation **(b) M beam end-Rotation angle Relation**

Fig. 10 Experimental Result of PL2 Specimen under Random Excitations (Kobe-20, 40-0.4)

DISCUSSION

Performance of lead damper

It is crucial to grasp whether the damper can deteriorate if the structure is subjected to moderate to severe earthquakes which can be expected during the service life or not, and how the dynamic response of the damper can be affected by the frequencies of the excitations, in order to establish damage free steel structural system. For this reason, the following characteristics are mainly examined based on the experimental result, that is, effects of excitation frequency and of repeated cyclic loading on the resisting force of the lead damper.

Effect of excitation frequency

Based on the sinusoidal excitation test result at identical tip deflection, the magnitudes of resisting force are compared as in Figs. 11 and 12. Here, about the ordinate in every figure, Pf denotes the average of the resisting forces in the stable regions of load-deformation curves for every cycle. In the figures, the symbols painted out blackly show the test results of descending loading paths, to distinguish the test results of ascending loading path, shown in the white omitted symbols. Figs. 11 and 12 illustrate the results of excitation tests carried out at constant tip deflection amplitudes of 20 and 40 mm, respectively. From the figures, it can be recognized that the resisting force of the damper is not so much susceptible to the sinusoidal excitation frequencies between the ranges from 0.5 to 2.5 Hz, though scatter of the Pf values can be a little observed among the specimens.

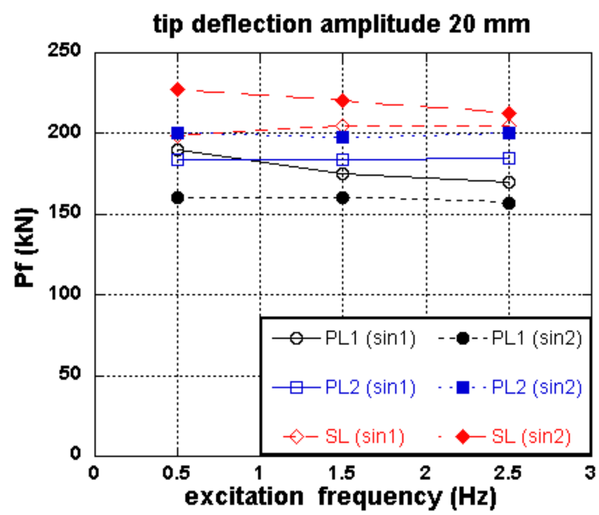


Fig. 11 Effect of Excitation Frequency on Resisting force (Tip Deflection Amp. 20 mm)

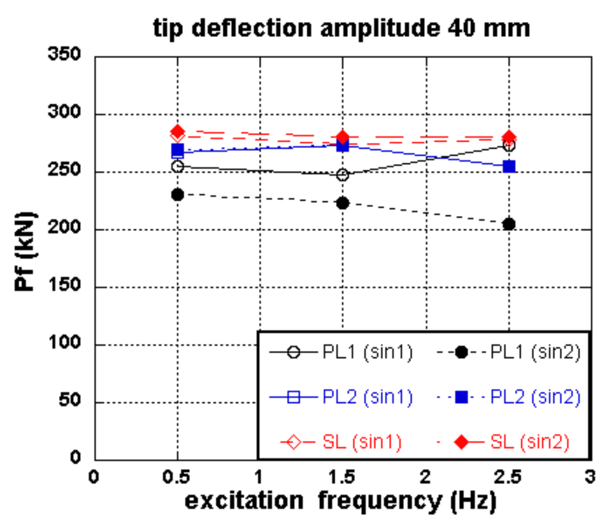


Fig. 12 Effect of Excitation Frequency on Resisting force (Tip Deflection Amp. 40 mm)

Next, in order to examine the effect of excitation frequency under random excitations, the load-deformation relations under input excitations with two different time histories are compared, as in Fig. 13. In this case, PL1 damper was excited initially by the input excitation of the loading path of El-40-0.6, and subsequently by the excitation of El-40-0.6-2, which was created by extending the duration of the former path by two times. According to the spectral analysis, the input wave of El-40-0.6 is predominant in frequency at about 1.2, 1.45 and 1.75 Hz. It can be seen that the load-deformation relation does not differ significantly from each other.

From the above discussion, it can be concluded that the variation of frequency of input excitation, within the range of static to at least 2.5 Hz, does not affect markedly the damper resisting force.

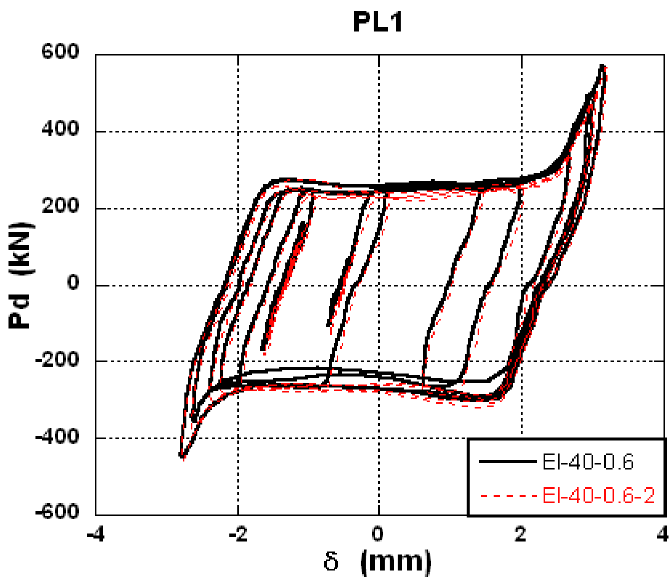


Fig. 13 Effect of Excitation Frequency under Random Excitation (PL1)

Effect of repeated cyclic loading

The possibility of deterioration on the resisting force of lead damper due to a number of repetitive loading can be also assessed from Figs. 11 and 12. Fig. 11 compares the magnitudes of resisting force Pf of PL1 damper subjected to identical sinusoidal excitations with tip deflection amplitude of 20 mm. The figure shows the results under loading steps of sin1 and sin2, respectively. In the latter step, the specimen has experienced more repetitive loading cycles of 90 cycles with larger tip deflection amplitudes than the former. Fig. 12 similarly shows the comparison between the resisting forces under the sinusoidal excitation of 40 mm tip deflection. In this case, the symbols painted out blackly show the results after experienced repetitive loading of more 40 cycles than the results shown in the white omitted symbols. In the figures, it has been verified that there is little or no degradation on the strength of the damper, even if the damper is subjected to repetitive loading at least over 40 cycles.

Effect of material property of damper

In the experiment, two types of materials were used in order to examine effect on the resisting force and durability of the damper. It has been shown that, on the resisting force, the specimen using the lead alloy is comparatively superior to the specimen of pure lead and is durable against the number of cyclic reversed loadings, as shown in Figs. 11 and 12. Here, a discussion is focused on the effect of material property on the response characteristic under random excitation. Fig.14 shows the hysteresis curves of PL1 and SL under identical random excitation of El-40-0.4. The figure indicates that SL specimen is comparatively larger in strength but smaller in deformation than PL specimen. This phenomenon means that the damper using lead alloy is preferable to secure necessary strength and at the same time, to lessen the lateral drift of the structure.

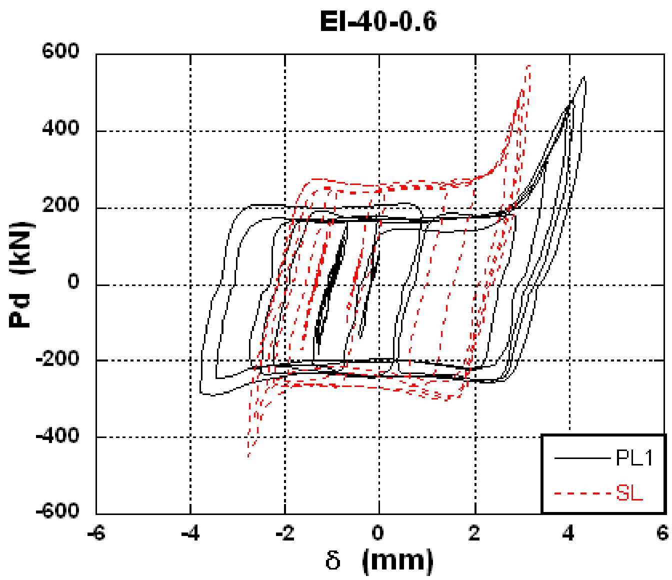


Fig. 14 Comparison of Hysteresis loops between PL and SL Specimens

CONCLUSION

In order to establish damage free system of steel structure in the event of earthquakes, a method to incorporate a developed lead damper into the beam splice has been proposed. The test for verifying the method has been carried out by using typical beam-column subassemblage, and the dynamic properties of the damper and the overall response characteristics of the subassemblage have been examined. From the test result, the following conclusions have been drawn.

(1) The structural detail to incorporate the lead damper into the beam splice is presented, and the practical usability can be confirmed by the experiment.

(2) The sinusoidal excitation tests, as well as the random excitation tests, has been performed in order to examine the effects of excitation frequency and the number of repetitive loading cycles on the resisting force, using two kinds of materials of lead with different chemical compositions. From the result of the sinusoidal excitation tests, it has been made clear that the resisting force-deformation relation of the damper is stable, without the influence of excitation frequency and the number of repetitive loadings of at least 90 cycles, in spite of the difference of materials. It has been shown that the hysteresis loop has the shape of parallelogram within the region of the deflection amplitude up to about 4 mm.

(3) Again, it has been also confirmed that the damper can respond stably within the deformation range of the damper up to about 4 mm, under random excitation. It has been recognized that the damper is quite sensitive against the excitations even with small to moderate magnitudes.

(4) After comparing the test results between two kinds of materials of lead, it has been recognized that the damper using lead alloy with antimony content is preferable to secure necessary strength and at

the same time, to lessen the lateral drift of the structure. However, when the deformation of the damper exceeds about 4mm, the resisting force increases rapidly near the reversal point. That is, a phenomenon so called as pinching is observed. Further research will be needed in order to suppress the pinching effect, because the response of the structure may change rapidly during earthquakes due to pinching effect of the damper and it may not guarantee that the members of the structure such as beams and columns can remain elastic during and after earthquakes.

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REFERENCES

1. Popov EP, Grigorian CE, Yang TS. "Developments in seismic structural analysis and design." Engineering Structures 1995; 17(3): 187-197.
2. Butterworth JW, "Seismic response of steel frames containing hierarchical friction dissipating joints." Mechanics of Structures and Materials, Bradford, Bridge & Foster (eds), 1999: 551-556.
3. Nomura S, Kohzu I, Amikawa T. "Fundamental study on damping capacity of lead bearing damper." J. Struct. Constr. Eng. AIJ 1999; 526: 153-160 (in Japanese).
4. Skinner RI, Robinson WH, McVerry GH. "An introduction to seismic isolation." John Wiley & Sons, 1993: 76 – 85.
5. Ogawa K, Tada M. "Computer program for static and dynamic analysis of steel frames considering the deformation of joint panel." Proc. of 17th Symposium on Computer technology of information, Systems and applications, Tokyo, Japan, AIJ 1994: 79-84 (in Japanese).