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RESPONSE OF HIGH-RISE BUILDING WITH LOW-YIELDING-STEEL DAMPERS

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SUMMARY

In Japan, hysteresis dampers using low-yielding-steel are applied to many high-rise buildings. Strain hardening of low-yielding-steel might have some influence on the building response property. Supposing the steel structure building of 30 stories with the equal mass and story height, the equivalent-shear type lumped-mass model of 30-mass, was set up, and dynamic response analysis was performed.
First, the influence of the building response caused by the restoring characteristic of low-yielding-steel dampers, were examined. Comparisons of the buildings response value were performed using the two-type models. One is the model in consideration of the damper strain hardening and the other is not. As a result, about the model not taking into consideration the damper strain hardening comparing with the model of the consideration, it was shown that the response reduction effect becomes small.
Next, the building supposed to experience earthquake motions of two or more times in a building lifetime. The influence of the strain hardening of low-yielding-steel dampers was examined on the building response property and the damper fatigue damage. When earthquake motions were applied repeatedly, the damper yielding force went up by strain hardening, and it was shown that the response value of building structure was reduced. Moreover, it was shown that the influence of the repeated earthquake motions affects the fatigue damage on dampers in small range.

1. Introduction

In recent years, many response control buildings using the low-yielding-steel came to be built in Japan. Low-yielding-steel is material with remarkable strain hardening after yielding. For this reason, when a building suffers an earthquake motion, depending on the plastic deformation of dampers, it is possible that the yielding force of dampers goes up by strain hardening, and does influence in the building response property. In this paper, the dynamic response analysis using the equivalent-shear-type model with low-yielding-steel dampers was carried out to examine the building response property. First, the modeling of low-yielding-steel dampers was examined checking the influence on the building response.

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The damper models were set to two types, one is considering the strain hardening and the Bauschinger effect, and the other is not considering them. We examined the difference among these models for the building response and the amount of energy absorption by dampers.
Next, using the models in consideration of strain hardening and the Bauschinger effect of low-yielding-steel, the influences of dampers were examined on the amount of dampers and damper rigidity for the building response property.
Finally, the building response property and the fatigue damage of dampers were examined supposing the case where the building was applied earthquake-motions repeatedly in the life.
Generally, the influence of the repeated earthquake-motions is not taken into consideration at the design of response control structures. In this paper, two or more times of earthquake inputs which differ in the levels, were inputted into the building, and it was examined how influence the number of repeated times and combination of them on the building response property.

2. Analysis Model and Seismic Input

2.1 Analysis Model

The analysis model outline is shown in Table 2.1, and the restoring characteristics are shown in Fig. 2.1. The analysis model set up the equivalent-shear-type model of 30-lumped-mass system, supposing the high-rise steel structure building. The building structure has the equal mass of 1.0 ts^2/cm and equal story height of 4.0 m.
The building structure is assumed to be elastic and the initial rigidity ${}_FK$ is set as the 1st natural period should be 3.75 seconds, and ${}_FK$ is distributed such as it is proportional by 1:3 from the top to the lowest story.
The initial damper rigidity ${}_DK_1$ is determined by the rigidity ratio ${}_K\alpha$ (= ${}_DK_1/{}_FK$). The rigidity ratio ${}_K\alpha$ is changed parametrically from 0.5 to 4.0, and the standard value was set to ${}_K\alpha$=2.0. The secondary rigidity ${}_DK_2$ was set to 1% of ${}_DK_1$. The 1st natural periods of the building in each rigidity ratio are shown in Table 2.2.
The yielding shear force of each story damper is computed by the damper-amount ${}_D\alpha$. The damper-amount ${}_D\alpha$ is defined as the ratio of the total damper yielding shear (${}_DQ_y$) to building total weight (Σw), namely ${}_D\alpha = {}_DQ_y/\Sigma w$. The each story value is determined as the straight-line distribution of 1:3 like the frame rigidity. ${}_D\alpha$ has been changed from 5 to 80%, and the standard value is ${}_D\alpha$=20%.
The viscous damping factor is 2% of rigidity proportionality type for the 1st natural period of building structure, and the damper member is considered to have histeresis damping only

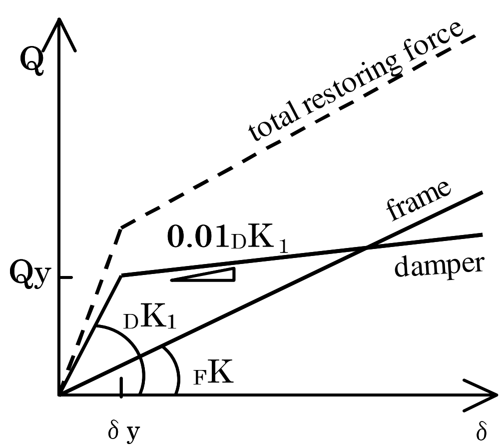


Fig. 2.1 Restoring force characteristics

Table 2.1 Analysis model

Frame	
mass	1.0 ts^2/ cm
story hight	4.0 m
natural period (1st)	${}_1T$=3.75sec
viscous damping value	${}_Fh$=2.0%
Damper	
initial rigidity	${}_DK_1 = {}_K\alpha \cdot {}_FK$
secondary rigidity	${}_DK_2$ = 0.01${}_DK_1$
damper- amount	${}_D\alpha = {}_DQ_y/\Sigma w$
viscous damping value	${}_Dh$=0%

Table 2.2 Natural period of 1st mode

${}_K\alpha$ (=${}_DK_1/{}_FK$)	0.5	1.0	2.0	3.0	4.0
${}_1T$ (sec)	3.1	2.7	2.2	1.9	1.7

2.2 Modeling of Damper Histeresis Characteristic

The histeresis characteristic of dampers is expressed by the skeleton part, the Bauschinger part, and elastic load-decreasing part, as shown in Fig. 2.2[1]. And it is defined using return-to-skeleton point Q', B_a point, and load- decreasing point Q'_{max}. Three kinds damper models (BL, SH1, SH2) were set up in modeling the restoring force curve, by the difference in modeling the strain hardening and the Bauschinger part.

BL model makes the histeresis characteristic two straight lines (bi-linear type), as shown in Fig. 2.3, and it is not taking the yielding force rising into consideration. This model is generally used in the dynamic response analysis of steel structure buildings.

SH1 model (Fig. 2.4) has made the return-to-skeleton point Q' in accordance with load-decreasing point Q'_{max} of a former cycle, and evaluates the yielding force rising by strain hardening. The Bauschinger part is simulated in two straight lines.

SH2 model (Fig. 2.5) sets up strain hardening alike the SH1 model, and approximates the Bauschinger part by two line segments divided by $_BQ'=0.8Q'$. The deflection δ_B of the Bauschinger part was taken as $\delta_B=0.15\ \Sigma\delta_S$ to the amount $\Sigma\delta_S$ of cumulative plastic deformation ratio of the skeleton part before the B_a point generating concerned, as shown in Fig. 2.5.

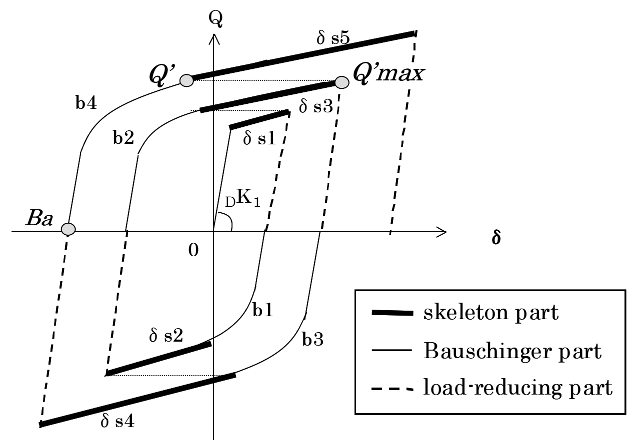


Fig. 2.2 Model of the damper restoring force [1]

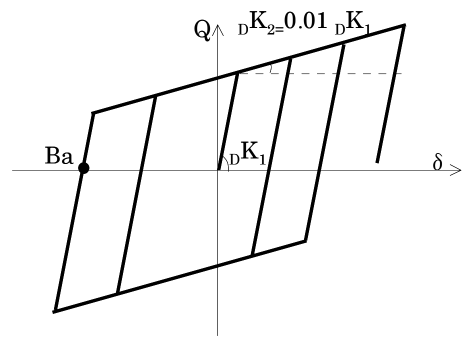


Fig. 2.3 Model BL

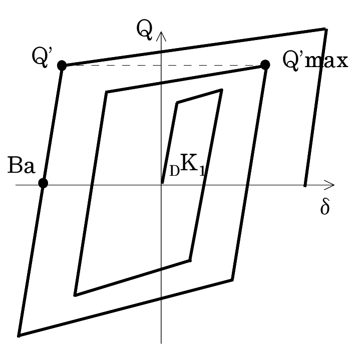


Fig. 2.4 Model SH1

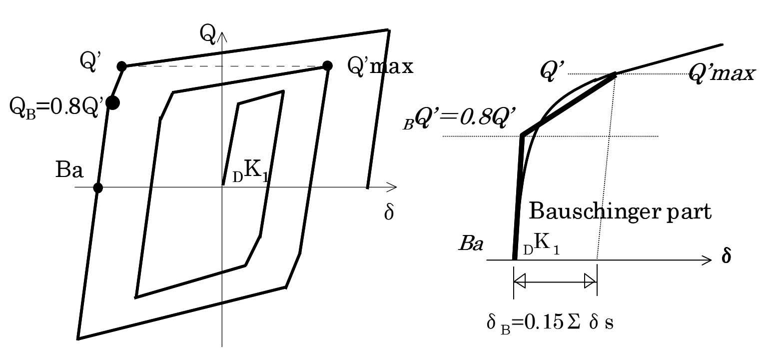


Fig. 2.5 Model SH2

2.3 Input Earthquake Motion

2 levels of input earthquake motions are set up. Level 1 (L1) earthquake motion is taken as an earthquake with the large possibility of occurring more than once in the building life. Level 2 (L2) earthquake motion is taken as to be the strongest among the earthquake motions which had experience in past, and the strongest earthquake motions which can be considered in future.
Three waves shown in Table 2.3 are used for the input earthquake waves. EL CENTRO 1940 NS and HACHINOHE 1968 Ns were normalized to the maximum velocity of 25 cm/s for L1 level and to 50 cm/s for L2 level. The artificial seismic wave ART WAVE 456[2] is the wave that the acceleration response spectrum is decided by the vibration characteristic coefficient Rt of the second type soil in Building Standard Law. It has the velocity response spectrum in a long period domain with Sv=125cm/s (for h= 0.02), and is made up using the phase characteristic of an observed earthquake motion. The maximum velocity is 27 cm/s for L1 level and 55 cm/s for L2 level. The velocity response spectrum of each seismic wave is shown in Fig. 2.6.

Table 2.2 Input earthquake motion

WAVE	Acceleration (Velocity)	
ART WAVE 456	138cm/ s^2 (27cm/ s)	276cm/ s^2 (25cm/ s)
EL CENTRO 1940 NS	245cm/ s^2 (25cm/ s)	490cm/ s^2 (50cm/ s)
HACHINOHE 1968 NS	167cm/ s^2 (25cm/ s)	334cm/ s^2 (50cm/ s)

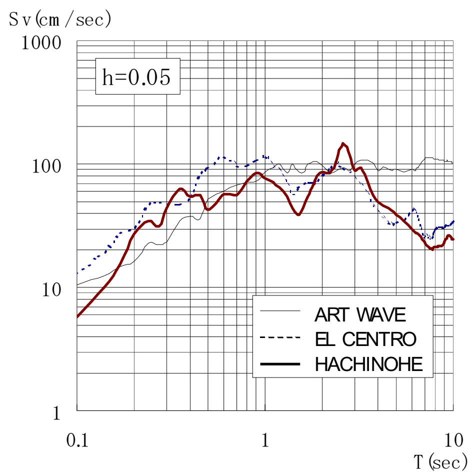


Fig. 2.6 Velocity response spectrum (h=0.05)

3. Influence of Restoring-force Models of Low-yielding-steel Dampers

In order to examine the influence of the restoring-force model of low-yielding-steel dampers on the building response property, dynamic response analysis was performed using BL model, SH1 model, and SH2 model. The input seismic wave is ART WAVE 456 and the input level is set to L2 and the damper rigidity ratio to ${}_{K}\alpha$=2.0.

3.1 Maximum Response Value

The maximum response story shear is shown in Fig. 3.1, the maximum story drift in Fig. 3.2, cumulative plastic deformation ratio in Fig. 3.3, and the amount of energy absorption by each story damper in Fig. 3.4.

The maximum response story shear becomes small in order of BL model, SH2 model, and SH1 model. The cumulative plastic deformation ratio of dampers became small in order of SH1 model, SH2 model, and BL model, and became the same tendency also about the amount of energy absorption.
Since BL model is not taking into consideration the yielding force rising by the strain hardening effect of dampers, it has few amounts of energy absorption than SH1 and SH2 model, and it is considered that the maximum story shear became small.
For this reason, the response values of each model are compared drawing the damper force vs. story drift curve. Amount of dampers ${}_{D}\alpha$ was change with 20%, 40%, and 60%. (See Fig. 3.5 - figure 3.7)
As for SH1 and SH2 model, the return-to-skeleton point is going up with the damper plastic deformation. This tendency is more remarkable in SH1 model which expresses the Bauschinger part by bi-linear. Moreover, the amount of rises of the return-to-skeleton point is so large when the amount of dampers is small.

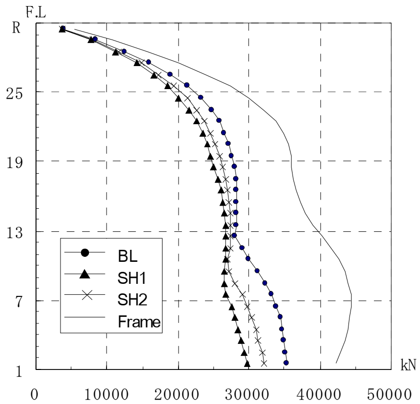


Fig. 3.1 Maximum story shear

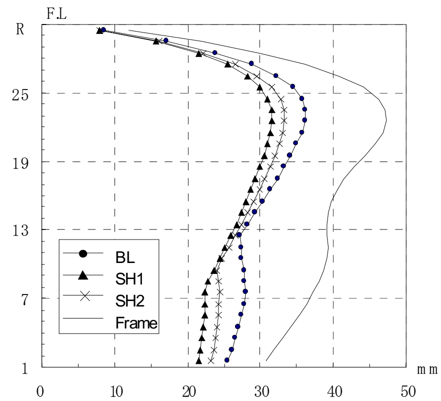


Fig. 3.2 Maximum story drift

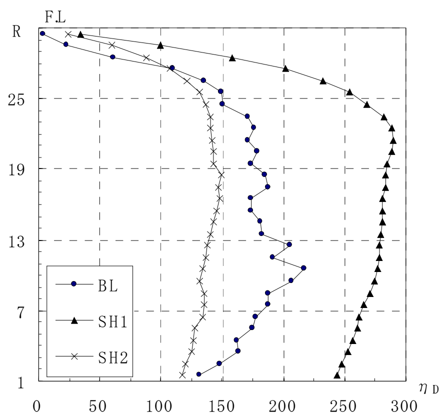


Fig. 3.3 Cumulative plastic deformation ratio

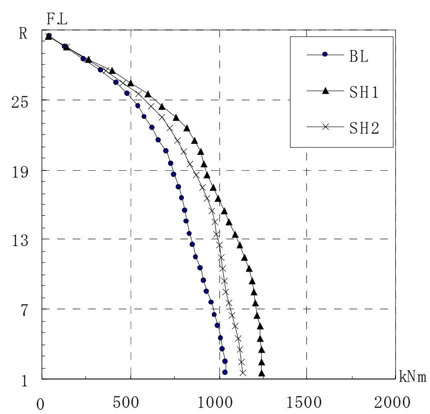


Fig. 3.4 amount of energy absorption

3.2 Influence of Restoring-force Characteristics

The damper cumulative plastic deformation ratio η_1 and the amount of energy absorption of a damper W_{p1} of the first story are shown in Table 3.1. η_1 of SH1 model is twice of BL model and the strain hardening influences the response value of dampers greatly.
Moreover, W_{p1} is increasing in order of BL model, SH2 model, and SH1 model. This tendency is the same when the amount of dampers increases. However, in order that η_1 may decrease, the difference of W_{p1} in each model decreases.

From the above mentioned, there are less amounts of energy absorption by BL model, since the influence of strain hardening is not taken into consideration, and it is thought that the response shear became large in each model. Since SH1 model and SH2 model are taking the influence of strain hardening into consideration, the amount of energy absorption of dampers is also larger than BL model, and the building response value also becomes small.
However, since SH1 model models the Bauschinger part in bi-linear, the amount of energy absorption is larger than SH2 model that has the restoring characteristic alike to the actual low-yielding-steel. So, if SH1 model is used, the response control effect of dampers may be evaluated excessively.
From these results, it is thought that SH2 model is appropriate as evaluating the damper restoring-force characteristic.

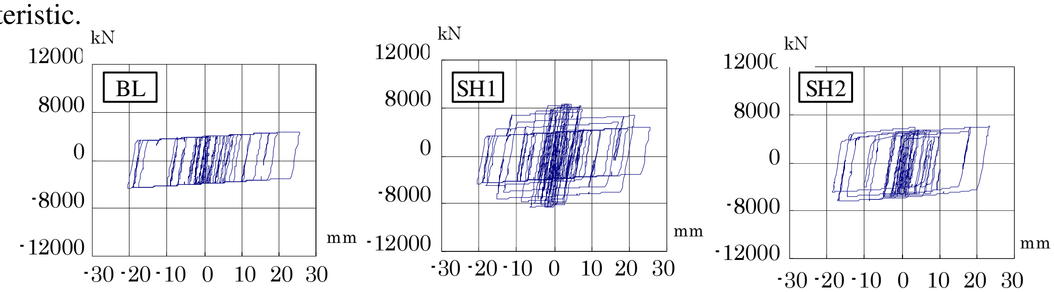


Fig. 3.5 1st story damper response history curve ${}_D\alpha$ =20%

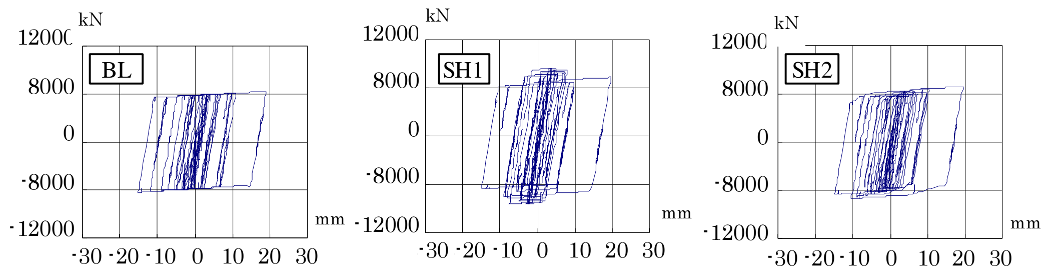


Fig. 3.6 1st story damper response history curve ${}_D\alpha$ =40%

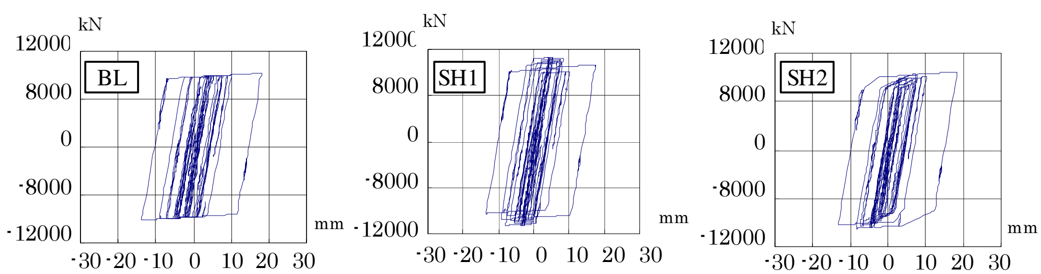


Fig. 3.7 1st story damper response history curve ${}_D\alpha$ =60%

Table 3.1 Maximum response value of 1st story damper

	Amount of energy absorption of the first story damper W_{p1} [kNm]		
Damper amount ${}_D\alpha$	20%	40%	60%
BL model	1.04×10^3	1.17×10^3	1.40×10^3
SH1 model	1.24×10^3	1.37×10^3	1.55×10^3
SH2 model	1.13×10^3	1.19×10^3	1.38×10^3

	Cumulative plastic deformation ratio of the first story damper		
Damper amount $_{D}\alpha$	20%	40%	60%
BL model	132	46.1	20.2
SH1 model	244	88.7	48.5
SH2 model	118	38.1	20.4

4. Influence of Repeated Earthquake Motion

4.1 Repeated Earthquake Input

The influence of repeated earthquake motions for the building response property is examined. SH2 model is used for the restoring-force characteristic of dampers based on the result of the former section. The concept of repeated earthquake inputs is shown in Fig. 4.1.

Generally, at the time of structural design, engineers are not taking into consideration the influence on the building response property or the damper fatigue damage caused by the repeated earthquake inputs in the life of the building. For this reason, the earthquake motions were input repeatedly to the building, supposing the combination of earthquake motions as shown in Table 4.1.

Moreover, the influence of repeated earthquake motions on dampers was taken into consideration by raising the return-to-skeleton point of dampers. In order to absorb the earthquake input energy, the dampers work in strain hardening, and the yielding strength goes up gradually.

For this reason, as shown in Fig. 4.2, the next input damper yielding forces are set to the maximum damper shears of the previous response value. Thus, the rise of yielding force is evaluated for the each response. But, the first and secondary rigidity are equivalent to the ones of initial input.

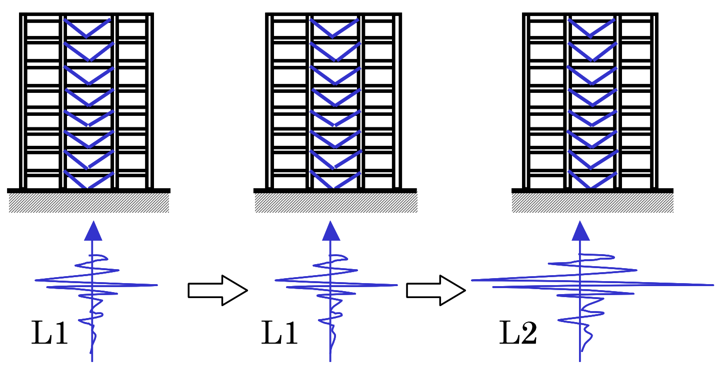


Fig. 4.1 Concept of repeated earthquake inputs

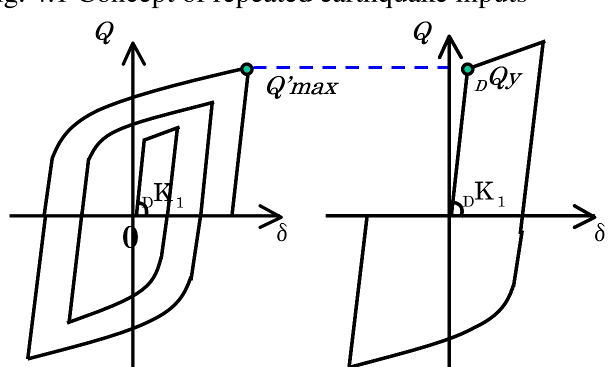


Fig. 4.2 Damper yielding force at the next input

Table 4.1 Combination of seismic inputs

Combination order of input level	Assumed earthquakes
Only L1	One minor earthquake
L1 → L1	Two minor earthquakes
L2 → L1	One minor earthquake after one big earthquake
Only L2	One big earthquake
L1 → L2	One big earthquake after one minor earthquake
L1 → L1 → L2	One big earthquake after two minor earthquakes

4.2 Response Characteristics

In Fig. 4.3, the maximum story shear response is shown, maximum story drift in Fig. 4.4, the cumulative plastic deformation ratio of dampers in Fig. 4.5, the amount of accumulated energy absorption of dampers in Fig. 4.6. (The input seismic wave is ART WAVE 456, ${}_D\alpha$=20%, ${}_K\alpha$=2.0)

When repeated earthquake inputs are applied, as for the story shear and story drift, it turns out that the maximum response values are reduced compared with the value of only L1 and only L2. (See Fig. 4.3, Fig. 4.4) That is, if there was much number of repeated inputs and the total energy input experienced in the whole building life was large, the response reduction became remarkable.

The cumulative plastic deformation ratio shown in Fig. 4.5 is the value that was totaled the cumulative plastic deformation ratio obtained in the earthquake inputs experienced by then. The cumulative plastic deformation ratio is influenced in order of the repeated inputs, and the values at L1 → L2 and L2 → L1 perfectly do not agree. This is considered because the damper yielding force changed from the initial input level, since the amounts of return-to-skeleton point raised differently.

The amount of the damper accumulated energy absorption by the repeated inputs was defined as the total value of the damper energy absorption obtained in the inputs experienced by then. (See of Fig. 4.6)

About the amount of the energy absorption in each stage, the value at L1 → L2 and L2 → L1 is mostly in accordance on each story. From this, it is thought that the amount of accumulated energy absorption can express only L1 as the simple sum of the value of only L2. In Figs. 4.7 to 4.9, the total amount accumulated energy absorption in the whole building was compared.

As a result of comparing the amount of energies at L1 → L2 and L2 → L1, it is thought that there are few differences and there is less influence of the input order. Moreover, these tendencies are same for all seismic waves.

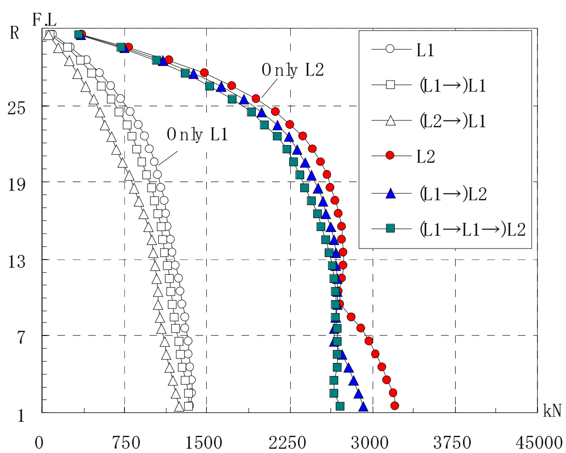


Fig. 4.3 Maximum shear of structure

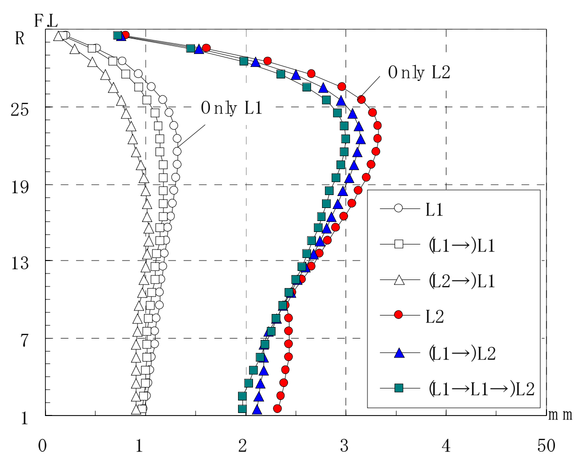


Fig. 4.4 Maximum story drift

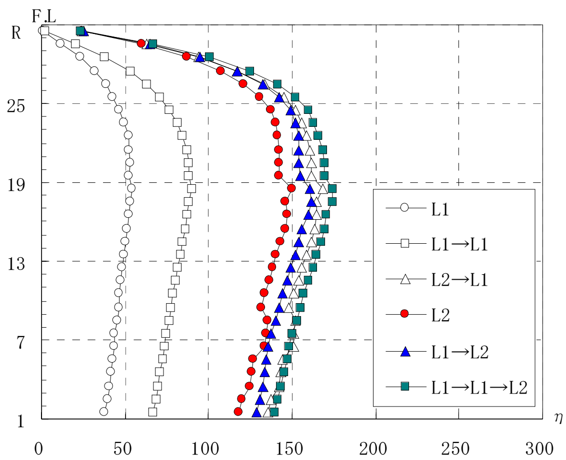


Fig. 4.5 Cumulative plastic deformation ratio of damper

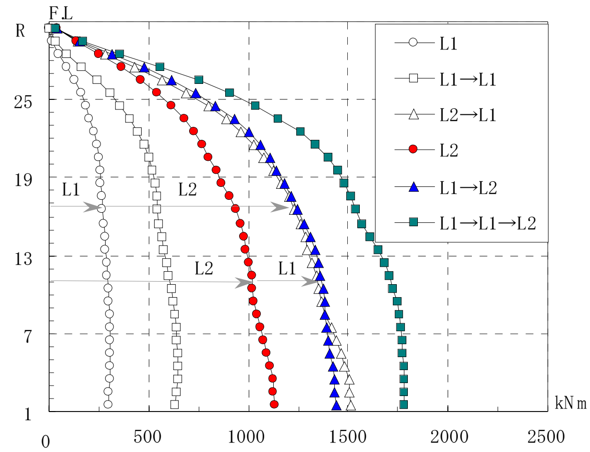
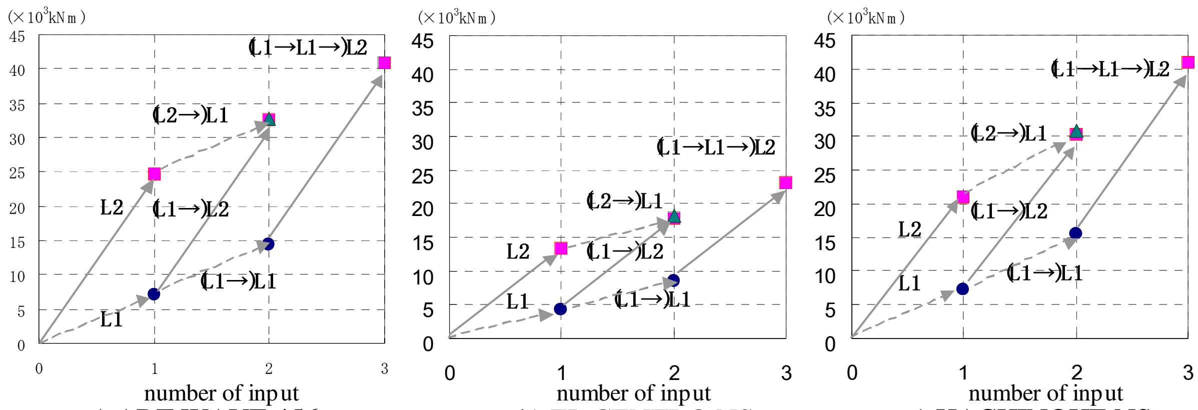


Fig. 4.6 Accumulation energy absorption



a) ART WAVE 456 b) EL CENTRO NS c) HACHINOHE NS

Fig. 4.7 Transition of energy absorption by repeated inputs

4.3 Examination by Response Ratio

When repeated earthquake motions were applied, the influence of the amount of dampers $_D\alpha$ and damper rigidity $_K\alpha$ were examined about building responses by various response ratios. The top displacement ratio (δ_{top}/δ) and the first story shear ratio (Q_D/Q) which are defined as the ratio of the response value with a damper to the response value of the damper-less building. Moreover, an energy absorption ratio was defined as the ratio of the input energy (E) to the total amount (W_p) of the energy that the damper absorbed.

(1) Influence by Amount of Damper ($_D\alpha$)

It was examined supposing $_K\alpha$=2.0 and the repeated inputs by ART WAVE by changing amount of dampers $_D\alpha$ from 20 to 80%. In Fig. 4.8, the comparison of each response ratio at the time of last L2 input are shown. In the case of the 20% of the amounts of dampers, reductions of response values are seen. When the damper return-to-skeleton point goes up by plastic deformation, it is thought that the response value decreased. However, there is little influence of the amount of dampers to the amount ratio of energy absorption.

(2) Influence by Rigidity Ratio ($_K\alpha$)

It was examined supposing $_D\alpha$ =20% and the repeated inputs by ART WAVE by changing damper rigidity ratio $_K\alpha$ from 0.5 to 2.0. In Fig. 4.9, the comparison of each response ratio at the time of last L2 input is shown.

About the top displacement, the reduction tendency of the response value by the repeated inputs has appeared. As for this, it is more remarkable when the rigidity ratio is higher. In the case where the amount of dampers changes, the energy absorption ratio value changes little by the repeated inputs, and it serves as an almost fixed value.

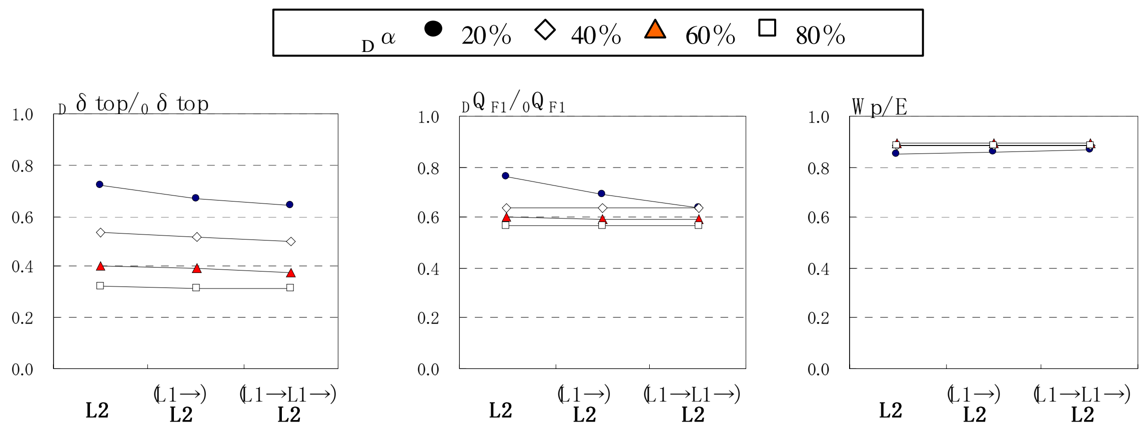


Fig. 4.8 Influence by amount of dampers (at the time of last L2 input)

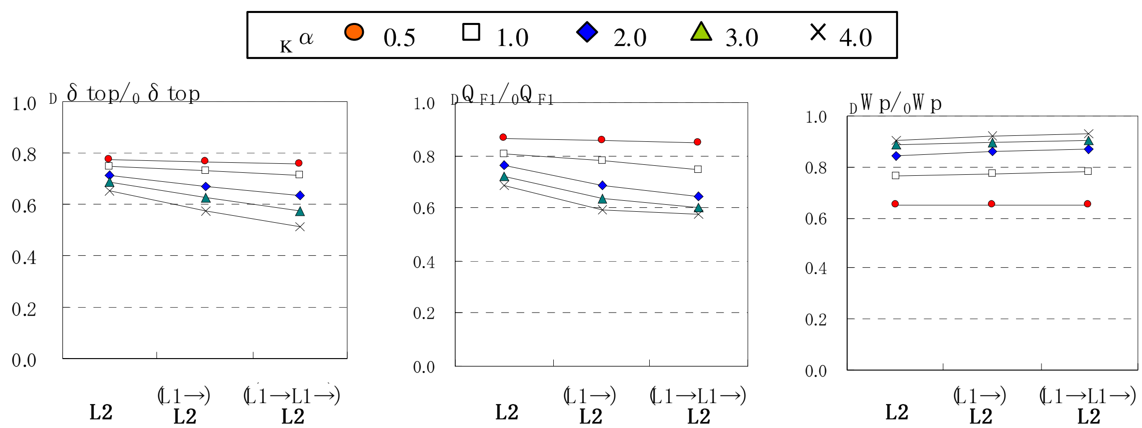


Fig. 4.9 Influence by rigidity of dampers (at the time of last L2 input)

5. Influence of Repeated Earthquake Input on Damper Fatigue Damage

The degree of accumulation fatigue damage and the damper safety were examined supposing the case where low-yielding-steel dampers receive large amplitude strain by the repeated earthquake inputs.

Generally, cumulative plastic deformation ratio, the ductility factor, etc. are used in many cases as the index showing the damper fatigue damage.

However, in accordance with the cumulative plastic deformation ratio etc., it is thought that the examination by the accumulation fatigue damage is also required in order to evaluate the damper fatigue damage under the building life. The technique generally used to the fatigue damage evaluation at the time of wind load is used, and the fatigue damage on the damper by the repeated inputs is considered.

5.1 Time History Response of Damper Axial Strain

The time history response of the damper axial strain was calculated from the 1st story drift obtained by dynamic response analysis.

The input seismic wave is ART WAVE 456. Amount of dampers $_D\alpha$ is set to 20% and damper rigidity ratio $_K\alpha$ is set to 2.0. The damper attached angle into the frame was supposed in two types (45 degrees and 60 degrees respectively). The calculation method of the axial strain of dampers about the case of 45 degrees is shown below.

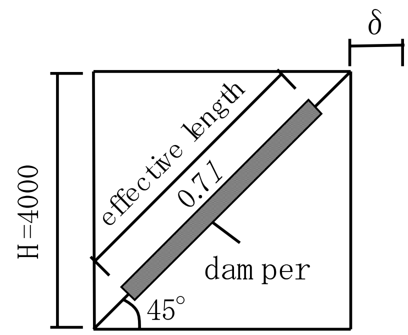
The time history response of the axial strain is shown in Fig. 5.1 about the case with the damper attached angle of 45 degrees at the time of the last input by the repeated input.

<u>45 degree attachment of damper</u>

Story height H=400 cm

effective length= $0.7l = 0.7 \times \sqrt{2}H$

original length l



If the story drift is set to δ, the damper axial displacement δ and damper strainε becomes as follows.

$$\Delta l = \frac{\delta}{\sqrt{2}H} \quad (1)$$

$$\varepsilon = \frac{\Delta l}{0.7l} = \frac{\delta}{0.7 \times 2H} = \frac{\delta}{560} \quad (2)$$

5.2 Damper Axial Strain Amplitude

The time history response of the damper axial strain obtained above, was calculated for the frequency (ni) of the strain amplitude in every 0.01%. The count of strain amplitude is based on the Rainflow method [3]. The frequency in every strain amplitude is shown in Fig. 5.2.

In the range of the strain amplitude exceeding yielding strain, it is about 100 times, and it is about several times below yielding strain. This tendency was the same even when repeated earthquake motions were applied.

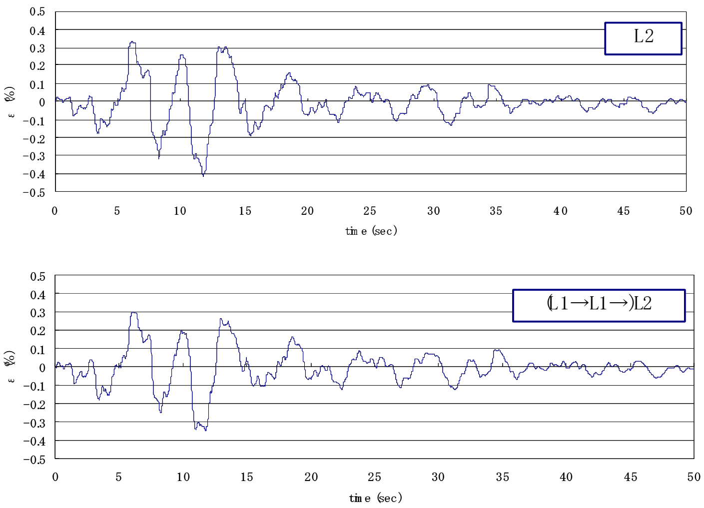


Fig. 5.1 Time history of damper axis strain
(45-degree last L2 input)

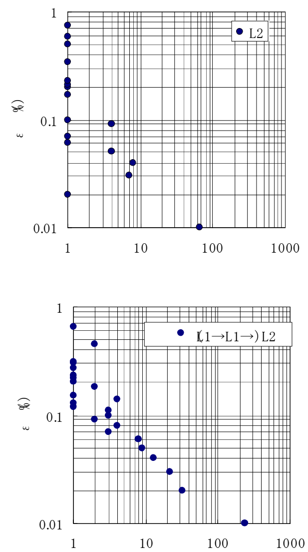


Fig. 5.2 Strain amplitude-frequency relation
(45-degree last L2 input)

5.3 Frequency of Strain Amplitude

Generally Miner's rule (the alignment accumulation damage rule) is usually used as the damage evaluation method of the damper for the wind load. Miner's rule can be expressed with the formula (3). When the sum total of the degree of accumulation fatigue damage is set to D= 1, it is predicted that a fatigue fracture arises.

$$D = \sum_i \frac{n_i}{N_i} \qquad (3)$$

Here

D: the degree of accumulation fatigue damage (D-value)

ni: frequency in a certain strain amplitude (times)

Ni: number of times when the fracture occurred at a strain-amplitude under the fixed amplitude loading

The value calculated in section 5.2 is used for the frequency ni. The number Ni of fracture repetitions is computed using the regression curve formula (2), which was obtained from the fatigue tests of low-yielding-steel buckling-constrained braces [4].

$$\varepsilon \times N_i^{0.3051} = 3.386 \qquad (4)$$

The accumulation fatigue damage value (D-value) of the damper by the repeated inputs is shown in Table 5.1. The accumulation fatigue damage value by the repeated inputs is not based on a damper attached angle, and is very small. D-value is about 1% at the maximum, and it is thought that it does not result in the fracture within the repeated conditions assumed in this paper.

Table 5.1 Accumulation fatigue damage value by repetition input (D-value)

	accumulation fatigue damage (D-value)	
	45°	60°
L1	0.06%	0.04%
L1→ L1	0.11%	0.07%
L2→ L1	1.37%	0.86%
L2	1.32%	0.83%
L1→ L2	1.04%	0.65%
L1→ L1→ L2	0.92%	0.58%

6. Conclusion

In this paper, we performed the dynamic response analysis of high-rise buildings with low-yielding-steel dampers, using the equivalent-shear type model for the purpose of grasping the response property. The equivalent-shear-type models of 30-mass system were used supposing the steel structure building of 30-stories.

First, the cases where the strain hardening is taken into consideration or not to the restoring force model of low-yielding-steel dampers were examined. Consequently, in the model in consideration of strain hardening, yielding force went up with the plastic deformation of dampers. Therefore, the response reduction effect of dampers was shown more highly, compared with the model that does not take strain hardening into consideration.

The influence of the repeated earthquake inputs was considered and the building response property and the fatigue damage of dampers were examined. In these cases, the model in consideration of strain hardening was used for the damper model. And the maximum response value of building structure showed the tendency to be reduced by the repeated earthquake inputs.

By the strain hardening accompanying plastic deformation of dampers, the damper yielding force goes up and a part of story shear for building structure was reduced.

Moreover, the amounts of damper energy absorption are not influenced by the input order in repeated earthquake inputs. And they can be evaluated as the simple sum of the energy absorbed by one time of the earthquake input.

In addition, as the result of evaluating how the repeated earthquake inputs affects the damper fatigue damage, the accumulation fatigue damage value was small and it turns out that dampers does not reach to the fatigue fracture by the earthquake input level and the number of times of which were assumed in this research.

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