SEISMIC SAFETY EVALUATION OF STEEL DAMPER FOR BASE ISOLATION

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ABSTRACT

The compact steel damper of varied cross section was developed as a seismic energy absorber and designed to be used in a base isolated nuclear power plant. Our experimental study using the one-third and full scaled models presented the unique fatigue curve implying the ultimate strength of the damper under low cyclic excitation. This paper discusses the evaluating method on seismic safety for our damper system, that is established through analytical procedure with designing data and the tested results for a steel material piece.

KEYWORDS

base isolation ; steel damper ; fatigue failure ; Miner's rule ; seismic safety ; bi-directional loading

INTRODUCTION

The base isolation technology has been revealed as a useful method for a massive and rigid structure to reduce its seismic input motion. The steel damper, developed as a seismic energy absorber and adopted with laminated rubber bearings, is one of the most effective systems which can be simply designed for a nuclear power plant (Fig.1). The compact steel damper of varied cross section shows high performance of plastic deformation and improved energy absorbing property (Kato et.al., 1993).

Our experimental study using the one-third and full scaled models presented stable force-displacement hysteretic characteristics. It also showed the unique fatigue curve implying the ultimate strength of the damper under low cyclic excitation. This paper discusses the evaluating method of the degree of seismic safety for our damper system. The ultimate behavior under severe seismic conditions is to be predicted based on the cumulative failure damage theory. The presented method will allow us to design the steel damper system incorporating its seismic margin given the design basic earthquake.
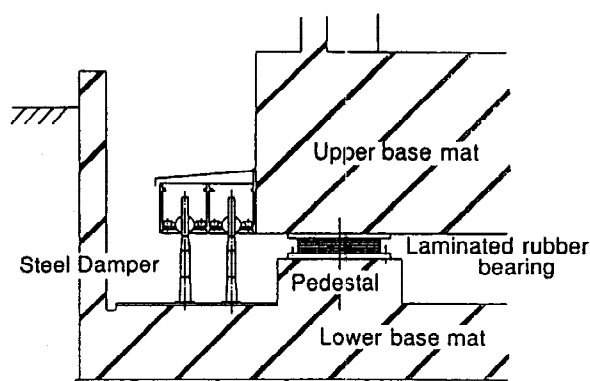

Fig.1 Schematic view of the base isolation system using steel dampers and laminated rubber bearings designed for a nuclear power plant.

EVALUATING METHOD

Flow diagram for the seismic safety evaluation of steel damper is shown in Fig.2. The evaluating procedure consists of two steps. First,shown as step 1 and 2, is the fatigue failure property of using the steel piece and steel damper's loading test and the analytical study. Second,shown as step 3, is the seismic safety evaluation using the cumulative damage factor by the Miner's rule and the verification test.
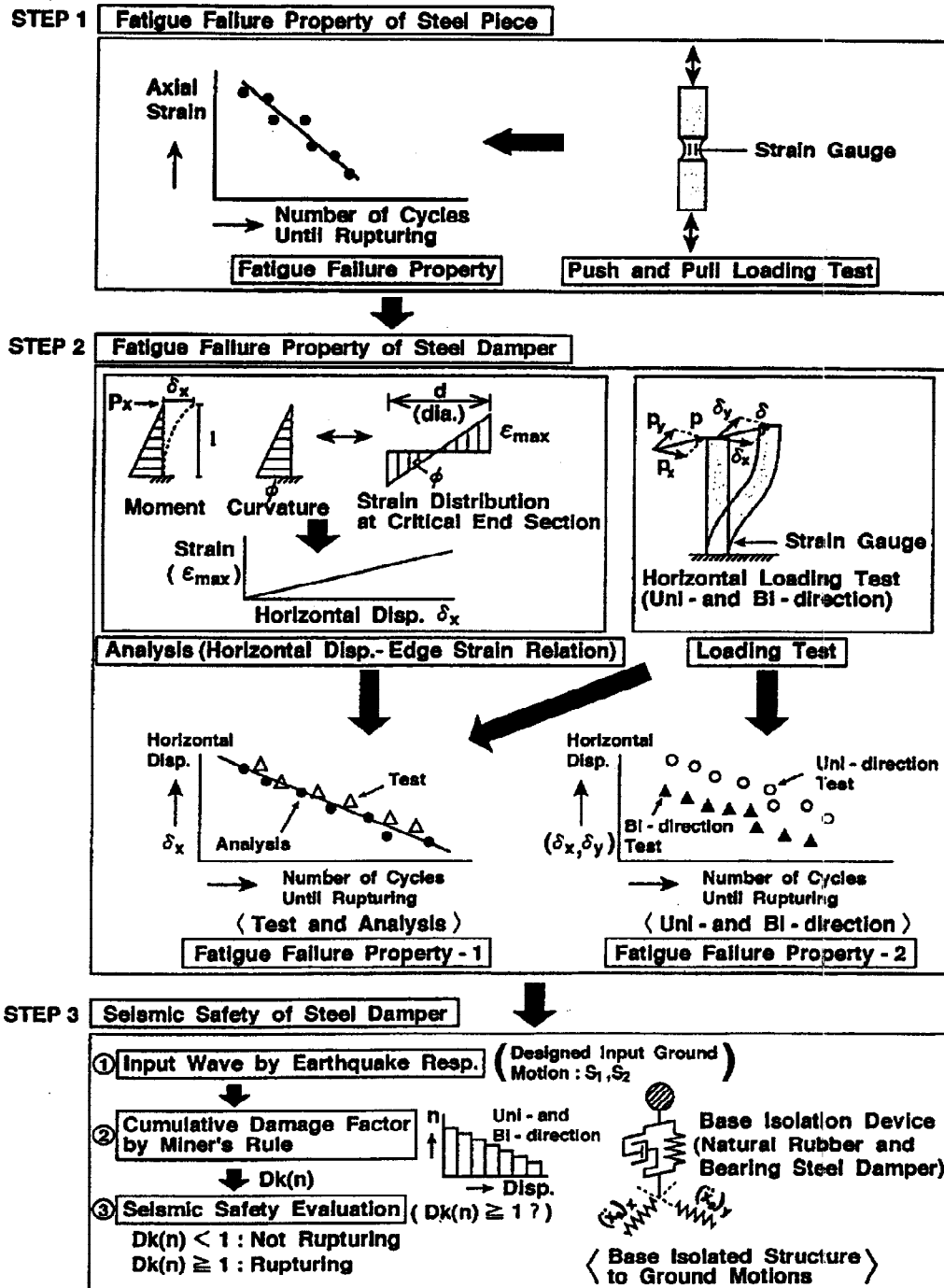

Fig.2 Evaluation procedure on seismic safety for a steel damper

FATIGUE FAILURE PROPERTY OF STEEL DAMPER

The fatigue failure property is defined between the lateral displacement amplitude and the number of loading cycles until rupturing. It is preferably obtained through analytical procedure with the designing data and tested results for a steel piece, not for the steel damper itself. In this section, the tested result for a steel piece is first presented, which is common in a material test, and is used in analytical study later. The predicted fatigue curve is compared with the experimental results obtained for our designed steel damper.

Test for Steel Piece

A steel material piece is tested under low cyclic load in the axial direction. The test piece of sand watch shape, shown in Fig.3, is loaded repeatedly until its rupturing. Mild steel (SS400) is employed as its material for obtainable ease. The tested result is shown in Fig.4 in terms of the fatigue failure curve for a steel material. It figures the relationship between the strain amplitude and the number of cycles associated with the strength of the material. In the figure, the straight line is drawn by the regression analysis for the dotted points. The number of cycles has logarithmic linear relation with the strain amplitude and it decreases with increasing strain amplitude. To be noted is that the estimated result has variety to some extent.
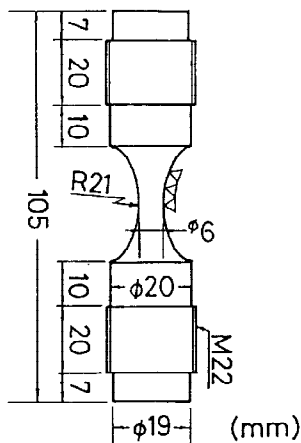

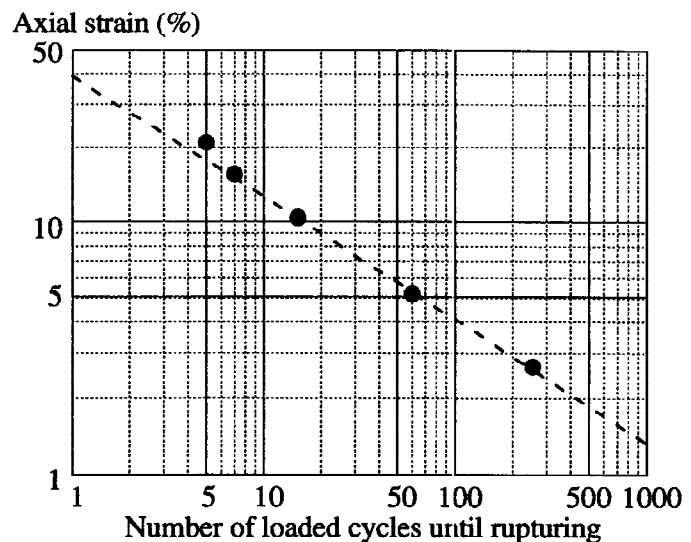Fig.3 Test piece of a steel material.

Fig.4 The fatigue failure curve for a steel material obtained by the regression analysis for the experimental results.

Experiment for Steel Damper

Our steel damper system is designed to cope with one-meter horizontal displacement and to keep enough capacity absorbing seismic energy. The system is composed of a steel beam of cantilever type and a spherical bearing, so can be replaced easily. The steel beam has varied cross section along its axial direction, that improves plastic deformability and energy-absorbing property. That allows us to use most part of the beam effectively and to reduce its size. The designing conditions are illustrated in Fig.5.

Experimental Items The experimental study is carried out using the one-third and full scaled models to obtain the fatigue failure property of the damper under cyclic lateral loads. The tested models and the tests setup are shown in Figs.6 and 7, respectively. Table 1 shows a list of experimental items and the number of tested models. In each case, loading is continued until the model ruptures. The items are of two cases, uni- and bi-directional loading cases. The latter is circular loading, which is most disadvantageous to the model.
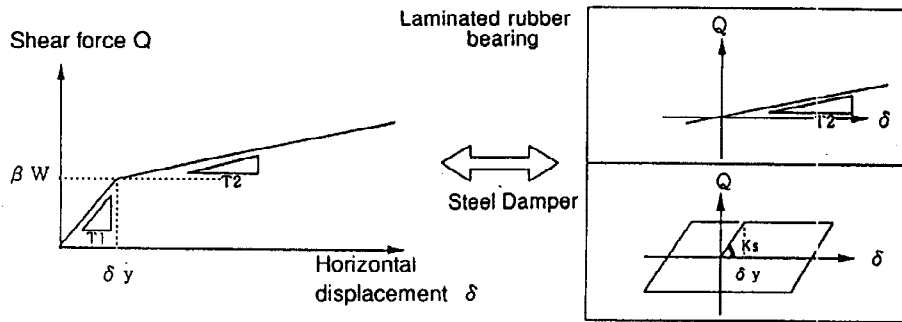
Fundermental period of Isdation Device T1 (sec)	Fundamental period of Rubber Bearing T2(sec)	Yield Coefficient	Viscous damping constant equivalent to S2 level(%)	Steel dampers (2 pcs)				Support Loading of Rubber Bearing (t)
				Spring constant Ks (t/cm)	Yield deflection δy (cm)	Critical deflection (cm)	Allowable end rotation angle of member (reference)	
1.0	2.0	0.1	9.5	15.1	2.48	100	45°	500

Fig.5 Fundamental hysteretic loop and the designing conditions of the base isolation system.
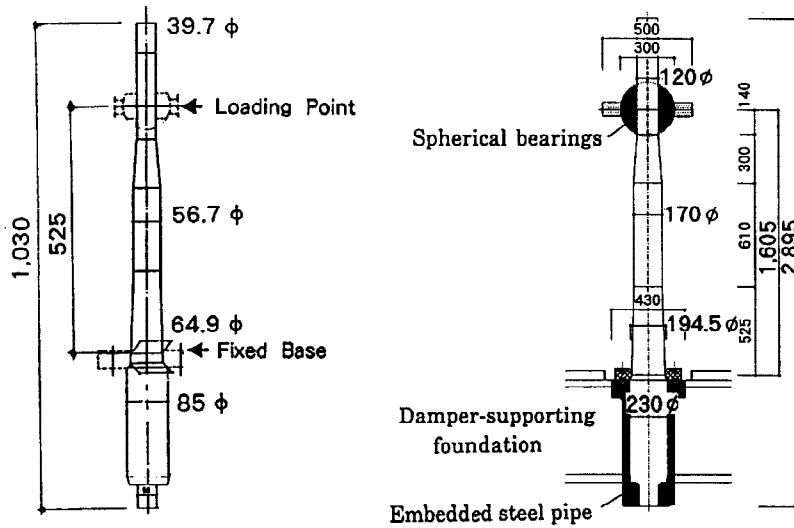
(a) One-third scaled model.   (b) Full scaled model.
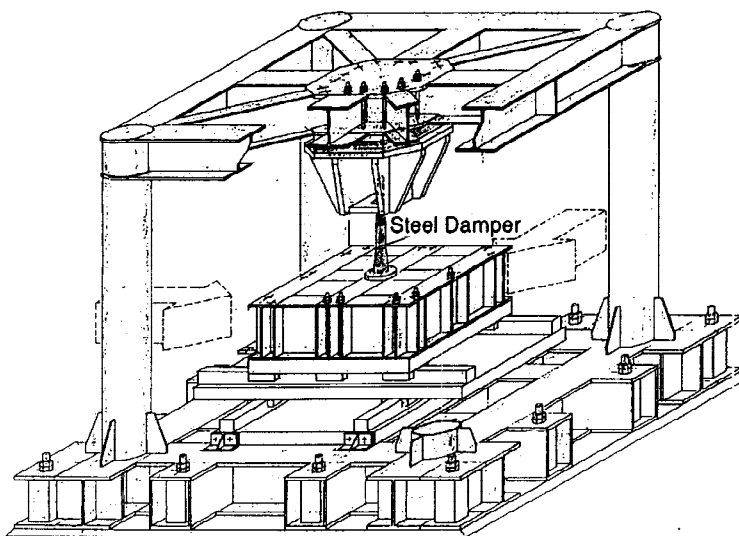
Fig.6 Tested models.

Fig.7 (a) Test setup of bi-directional loading for one-third scaled model.
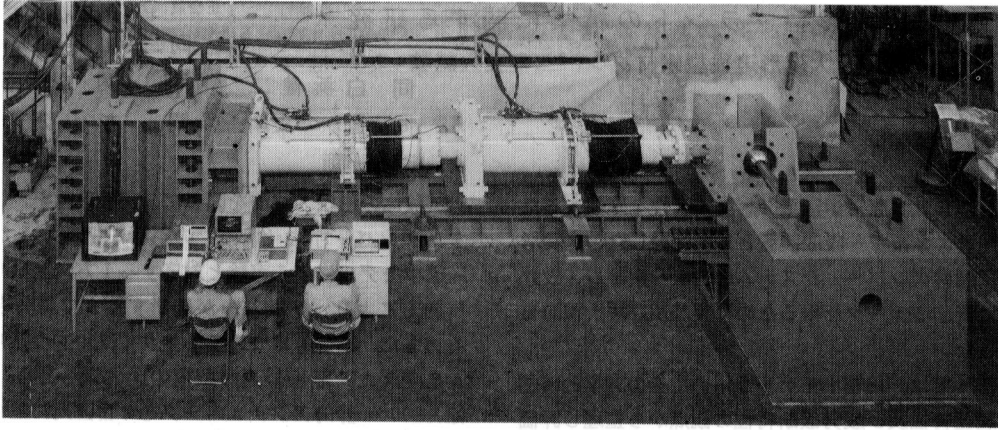
Fig.7 (b) Test setup of uni-directional loading for full scaled model.

Table 1 Experimental items and the number of tested models.

Loading direction	Scale of tested model	Input level[*1]					
		1/2 S_2	3/5 S_2	S_2[*2]	3/2 S_2	2 S_2	2 S_2
		5 cm (15 cm)[*3]	9 cm (27 cm)	15 cm (45 cm)	20 cm (60 cm)	25 cm (75 cm)	28 cm (84 cm)
1-	1/3	2	2	2	1	1	1
	1/1	—	—	—	—	1 (70 cm)	—
2- (circular)	1/3	2	2	2	1	—	—

*1 displacement amplitude of uni-directional loading or the radius of circular loading
*2 S_2 is the maximum displacement amplitude level for the ultimate design basic earthquake input motion.
*3 (.) is the amplitude converted to full scale.

Experimental results Fig.8 shows the fatigue failure curves obtained by the regression analysis for the dotted experimental results in the relation between the displacement amplitude and the number of loading cycles until rupturing. For both uni- and bi-directional loading cases, the above relation is characterized as logarithmic linearity. However, the number of cycles for circular loading is almost a half of that for uni-directional case in each amplitude level. This relation is explained by the amount of energy which the damper absorbs. The energy for circular loading is twice as much as that for uni-directional loading. The dotted result for the full scaled model implies independency of the fatigue failure property on the scale of the model.
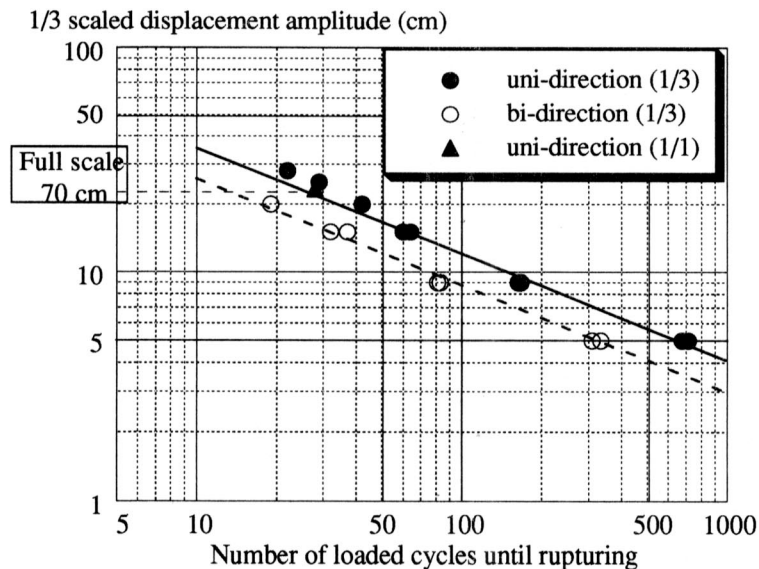

Fig.8 Fatigue failure curves obtained from the experimental results for the steel damper.

Analytical study

For a cantilever type of steel bar, the curvature in each cross-section shows the proportional distribution to the triangular moment distribution along the axial direction. The amount of deformation at the free edge is calculated by integrating the curvature distribution over the length of a bar. Assuming plane kept under deformation, the maximum strain in each section is determined from the linear relation between strain and curvature. As a result, the displacement amplitude at the free edge is expressed in terms of the maximum strain at the fixed end.

Fig.9 shows the strain distribution at the edge of each section along the axial direction. In the figure, the broken lines show the results of uni-directional initial loading test for the one-third model, which are obtained for several displacement amplitudes. The straight lines are the analytical results based on the above assumption with the effective diameter (56.7 mm) of the damper. The experimental results show the efficiency of varied section avoiding the concentration of strain at the fixed end.
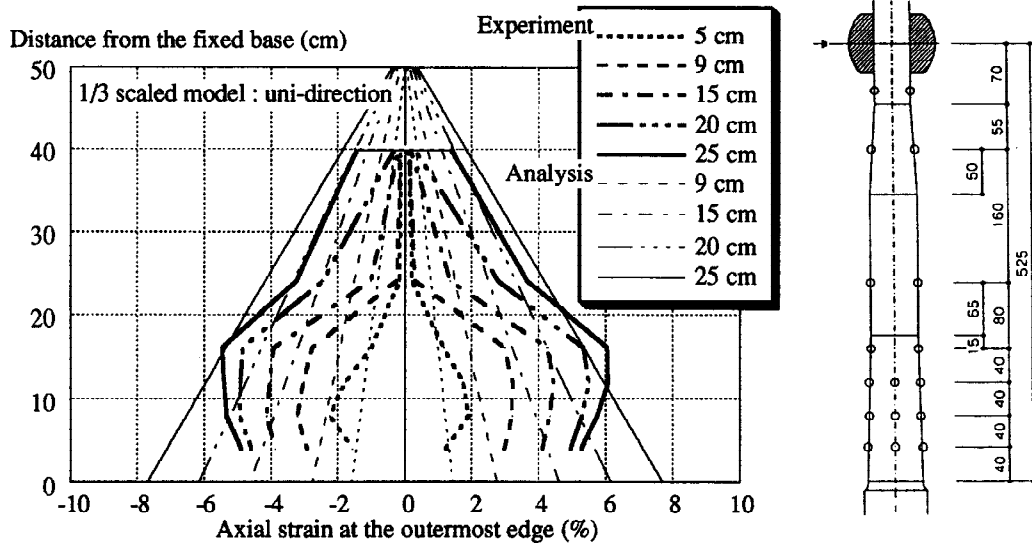

Fig.9 Strain distribution at the edge of each section along the axial direction.
(Comparison between the experimental results and the analytical assumption.)

Using the assumed relationship between the lateral displacement and the maximum strain, the fatigue failure curve for a steel material can be converted to that for a steel damper. Fig.10 shows the comparison between
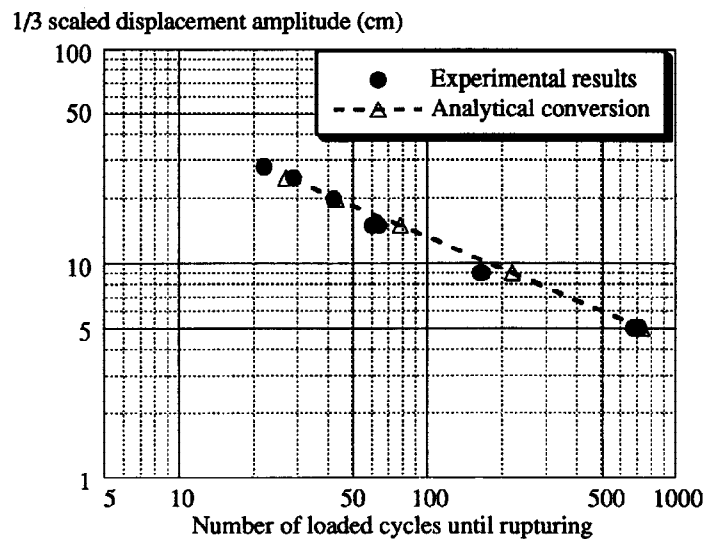

Fig.10 Comparison in fatigue failure curves between the result obtained from analytical conversion of tested data for a steel material and the experimental result for the steel damper.

the experimental result for the one-third model in a uni-directional loading case and the analytically converted result from the tested data for a steel material. The figure shows good agreement in those results. The analytical strain distribution for a steel bar apparently averages out the result for the varied-section damper, however, the assumed maximum strain at the critical end is interpreted as equivalent to the strain level dominating the fatigue failure property.

SEISMIC SAFETY OF STEEL DAMPER

Evaluating the degree of seismic safety for the steel damper employs the cumulative fatigue damage theory based on the Miner's rule (Miner, 1945). It defines that failure occurs at the moment of the cumulative damage factor being 1.0. The verification test is planed to apply this theory to seismic excitation.

Experiment on Seismic Response

The one-third damper model is excited in both uni- and bi-direction assuming the seismic response of the base isolated structure. The input wave form is derived from the earthquake response analysis for the artificial S2 and 2 times S2 level input motion (Kato et.al., 1990). In the analysis, one lumped mass model is used incorporating the basic properties of the isolation system as shown in Fig.5. The semi-static excitation is applied repeatedly till the damper ruptures. Fig.11 shows the example of the input displacement wave in real time history.
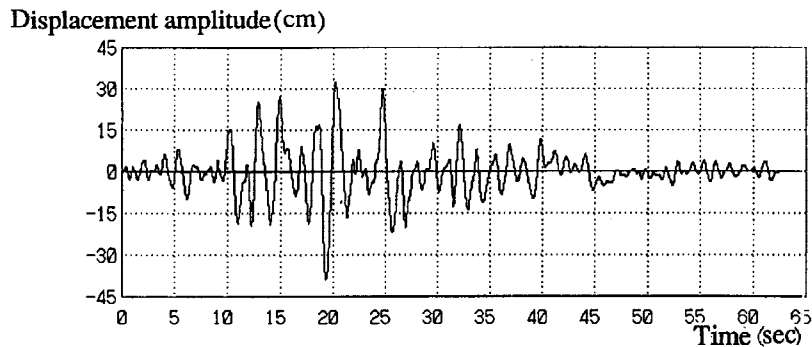
Displacement amplitude(cm)

Fig.11 S2 level response displacement wave applied to the damper model.

Cumulative Damage Evaluation

The fatigue curve obtained above is defined as the following equation.

$$\delta \cdot N_f{}^a = b$$

where, δ : displacement amplitude
   N_f : number of cycles until rupturing
   a, b : constants

The cumulative damage factor is calculated as follows based on the Miner's rule.

$$D_k(n) = \sum_{i=1}^{k} n_i/N_{fi} = \sum_{i=1}^{k} \left\{ (\delta_i/b)^{1/a} \times n_i \right\}$$

where, δ_i : displacement amplitude
   n_i : number of cycles actually repeated with δ_i
   N_{fi} : number of cycles with δ_i until rupturing

Fig.12 shows the histogram decomposing the input displacement wave into amplitudes from one peak to the next peak, which are the indices in calculating the cumulative damage factor. In Fig.13, the distribution of

the damage factor is illustrated for the displacement amplitude. The factor for relatively large amplitude is dominant for the total factor. From the analytical result shown in Table 2, it is appropriate to define fatigue rupturing with the cumulative damage factor of one.
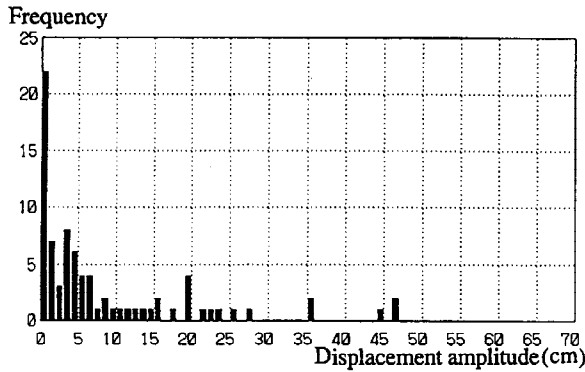

Fig.12 Frequency distribution of peak to peak amplitude in the input displacement wave.
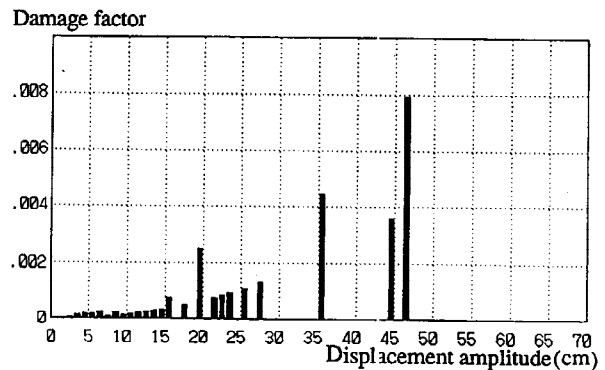

Fig.13 Distribution of the damage factor for the displacement amplitude.

Table 2 Analytical study on the cumulative damage factor for the experimental result.

Loading direction	Input level	Maximum displacement	Cumulative damage factor per a wave	Number of input waves till rupturing	Cumulative damage factor till rupturing
1-	S2	12.3 cm	0.025	40	1.002
	2×S2	24.6 cm	0.113	9	1.013
2-	S2	13.3 cm	0.056	20	1.084
	2×S2	26.6 cm	0.252	5	1.152

CONCLUDING REMARKS

Trough the work presented above, the following lines have been identified as conclusions ;
(1) The evaluating method on seismic safety for the damper system is established through analytical procedure with designing data and the tested results for a steel material piece.
(2) Fatigue failure process of the steel damper system can be predicted by the cumulative damage theory for seismic response excitation.
(3) The cumulative damage factor can be applied for both uni- and bi-directional lateral loading associated with the amount of absorbed energy.

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