AN APPLICATION OF AN ELASTOPLASTIC DAMPER UTILIZING CONTINUOUS PLASTIC BENDING OF METAL RODS TO AN APPARATUS IN A BUILDING

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SUMMARY

A new type of elastoplastic damper utilizing continuous plastic bending of thin metal rods was developed. The elastoplastic damper is composed of two racks, four pinions, some thin metal rods, two rollers which wind the rods around, and guide rollers. This elastoplastic damper yields damping for a small displacement as well as a large displacement. The trial damper was made and the resisting force characteristics and the fatigue strength of the damper were measured making use of a shaking table. The metal rods used here were aluminum, copper and steel rods of 2 mm or 3 mm in diameter. The results of the fatigue life tests showed that metal rods broke at the number of cycles more than 1000 regardless of rod materials and the vibration amplitudes. The hysteretic characteristics of the elastoplastic damper can be assumed to be bi-linear type based on the experimental results of the vibration tests. Seismic responses of an L-shaped pipe supported by the elastoplastic damper were measured using an electrohydraulic type shaking table, and compared with the calculated results. The response spectra of an apparatus supported by the damper and subjected to seismic floor response waves in a building were calculated, and the designing indexes for the apparatus-isolation system were shown.

INTRODUCTION

In recent years, some elastoplastic dampers have been developed to restrain the deflections of piping systems attached to the wall or an apparatus placed on a floor in a building under the seismic [for example: Ohmata, et al., 1994; Ohmata, et al., 1995; Shibata, et al., 1991; Skinner, et al., 1993]. The feature of elastoplastic dampers is simple in construction and inexpensive. However, they have a drawback that they give very little damping in a small displacement. In this paper, a new type of elastoplastic damper which gives damping even in a small displacement is proposed.

The damper utilizes continuous plastic bending of thin metal rods. A trial elastoplastic damper was made and its resisting force characteristics was measured. The experimental results are compared with the calculated results. The fatigute strength of the damper was also measured. The seismic responses of an

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L-shaped pipe supported by the elastoplastic damper were measured using an electrohydraulic type shaking table, and the effects of the damper on the deflection of the pipe are discussed. The experimental results were compared with the calculated results, and the validity of the calculations is substantiated.

Next, the case in which the elastoplastic damper is attached to an apparatus placed on a floor in a building was considered, and seismic floor response spectra in connection with designing process for the apparatus-isolation system were examined. Using the response spectra, designing indexes for the apparatus-isolation system are shown.

2. CONSTRUCTION OF THE ELASTOPLASTIC DAMPER

Fig. 1 shows the conceptional sketch of the elastoplastic damper which utilizes continuous plastic bending of thin metel rods. It is composed of two racks, four pinions, some thin metal rods and two rollers which wind the rods around, and guide rollers. When a relative linear motion is made between the upper and lower rod ends, the rollers rotate because of the racks and the pinions. Some thin metal rods which are parallel to each other are wound on the upper or lower rotating rollers in a condition of plastic bending, so that a constant resisting force will be obtained, i.e. the damper will show the elastoplastic characteristics.

The resisting force can be given by

$$Fs = 2nMp \,/\, r \tag{1}$$

where n is the number of rod, and r is the pitch radius of the pinion. The value of 2 in Eq. (1) means that the plastic deformation of each rod occurs on two rollers. However, Fs will become smaller than Eq.(1) if the rods are not completely tighten. Mp denotes the fully plastic moment of a rod and is given by

$$Mp = d^3 \sigma y \,/\, 6 \tag{2}$$

where d and σy are the diameter and the yield stress of the rod, respectively. The condition to cause plastic deformation to the metal rod on the two rollers is given by

$$R < \mathrm{EI} \,/\, Mp \tag{3}$$

where R is the radius of the roller. The idealized force-displacement curve of the damper is shown in Fig. 2.

The stiffness ke in the elastic region of the elastoplastic damper is given by

$$ke = (R/r)^2 (nAE/L) \tag{4}$$

where A is the cross-sectional area of rod and L is the length between the rollers.

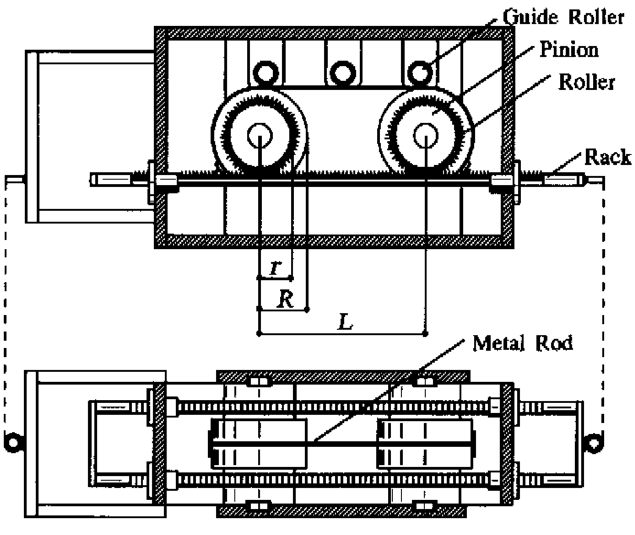


Figure 1: Conceptional sketch of the elastoplastic damper

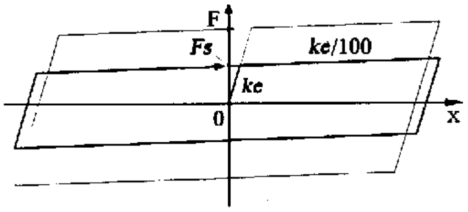


Figure 2: Idealized force-displacement curve of the elastoplastic damper

3. HYSTERESIS LOOP AND FATIGUE STRENGTH OF THE DAMPER

A trial elastoplastic damper was made using aluminum or copper rods of 2 mm or 3 mm in diameter, R = 25 mm, r = 17.5 mm, L = 80 mm and n = 1. The damper was attached between a shaking table and a rigid wall through a load cell. The experimental apparatus is shown in Fig. 3.

3.1 Resisting Force Characteristics

First, the resisting force characteristics were measured. The displacement of the shaking table was measured by an inductance-type displacement transducer. Fig. 4 shows the hysteresis curves of the damper when it was subjected to sinusoidal displacements of frequency 1 Hz and amplitudes 5 mm, 10 mm, 15 mm and 20 mm. It will be seen from Fig. 4 that the resisting force characteristics of the damper are similar to Fig. 2, and the damper gives damping in a small displacement as well as a large displacement.

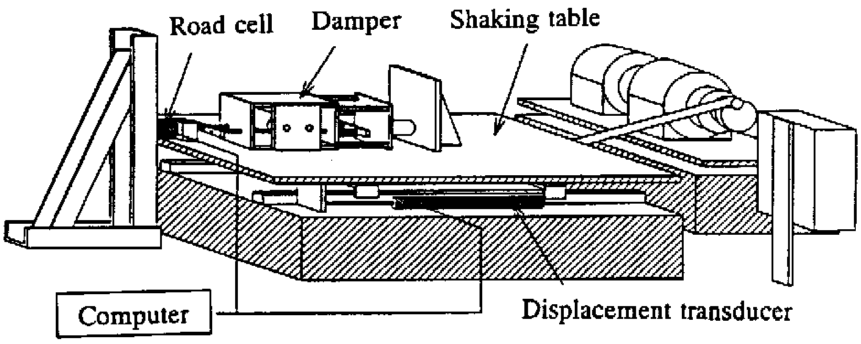
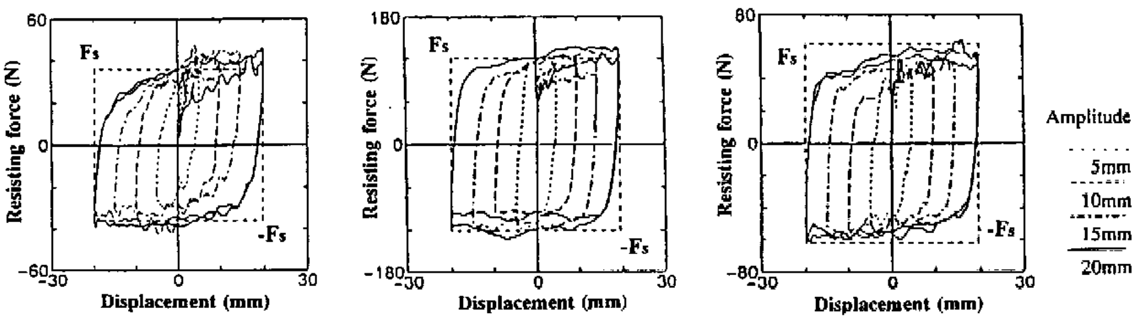


Figure 3: Experimental apparatus

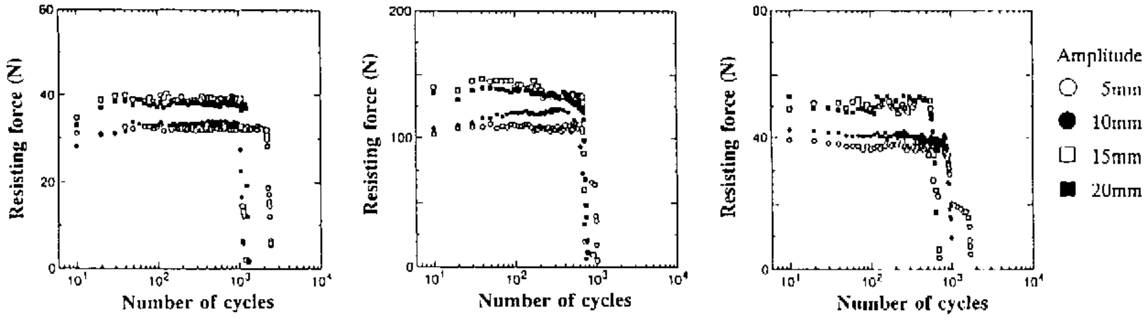


a) Copper (ϕ 2mm) b) Copper(ϕ 3mm) c) Aluminum (ϕ 3mm)

Figure 4: Hysteresis curves of the elastoplastic damper

3.2 Fatigue Strength of a Rod

Next, the relation between the number of cycles and the maximum resisting force of the damper until the rods broke off was measured using the experimental apparatus shown in Fig. 3. It was subject to sinusoidal displacements of frequency 1 Hz and amplitudes 5 mm, 10 mm, 15 mm and 20 mm. The experimental results are shown in Fig. 5. It is clear from Fig. 5 that the fatigue strength of a rod increases as the diameter or the amplitude of a sinusoidal displacement decreases, and a metal rod brakes at the number of cycles more than 1000 regardless of rod materials and the vibration amplitudes.



a) Copper (ϕ 2mm) b) Copper(ϕ 3mm) c) Aluminum (ϕ 3mm)

Figure 5: Fatigue life of the rods

4. SEISMIC RESPONSES OF AN L-SHAPED PIPE SUPPORTED BY THE DAMPER

4.1 Equations of Motion

Let us consider a case in which the elastoplastic damper is attached to the corner of an L-shaped pipe and the foundation is subjected to a seismic excitation $\ddot{z}$. Fig. 6 shows the analytical model of the L-shaped pipe. The L-shaped pipe is replaced by a n-mass system in which the masses are placed at equal intervals linked by massless leaf spring. The equations of motion in matrix form are given by

$$\{\ddot{u}\} = -[M]^{-1}([A]^{-1}\{u\} + \{F\}) - \{\ddot{z}\} \quad (5)$$

here $\{u\} = (\{y\} - \{z\})$ is the relative displacement vector, $\{y\}$ is the absolute displacement vector, $\{\ddot{z}\}$ is the input acceleration vector, and $\{F\}$ is the resisting forced vector, and they are given by

$$\{u\} = \{u_1, \cdots\cdots, u_n\}^T, \quad \{y\}=\{y_1, \cdots\cdots, y_n\}^T, \{\ddot{z}\} = \{\ddot{z}, \cdots\cdots, \ddot{z}\}^T, \{F\} = \{0, \cdots, f_i, \cdots, 0\}^T$$

f_i is the resisting force of the damper which is equal to Fs given by Eq.(1). $[M]$ and $[A]$ are the mass matrix and the influence coefficient matrix, respectively.

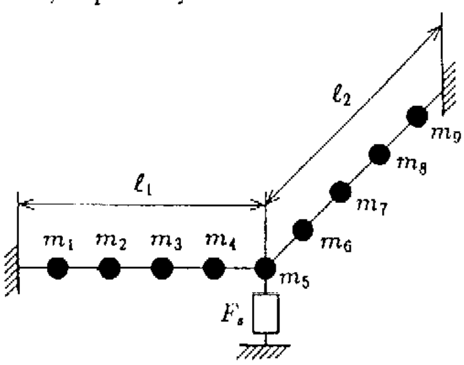


Figure 6: Analytical model of the L-shaped pipe

4.2 Numerical Examples

Eq.(5) was programmed using a continuous system simulation language (FUJITSU SLCS5). The numerical integration method used here is the 4th order Runge-Kutta method. The input seismic waves are El Centro (1940) NS and Akita (1983) NS normalized to be 0.5 m/s², 1.0 m/s², 2.0 m/s² and 3.0 m/s² at the maximum acceleration.

The numerical conditions of the pipe and the damper are given in Table 1. The pipe was replaced by a nine-mass system and the damper was attached to the 5th mass. The calculations were carried out for aluminum or copper rods of 3 mm in diameter. The maximum deflections of the pipe at the corner (i.e. the 5th mass) in the calculations both with the damper and without the damper are shown in Table 2. It will be seen from Table 2 that the maximum deflection at the corner of the pipe decreases to between 1/3 and 1/8 in comparison to that of the calculations without the damper. Therefore, it is apparent that this elastoplastic damper is effective for a small displacement as well as a large displacement.

Table 1: Experimental condition of the L-shaped pipe

Material	STPG42
Outside diameter	60.5 mm
Wall thickness	5.5 mm
Length l_1, l_2	3000 mm
Mass par meter	7.65 kg/m
1st natural frequency	5.00 Hz

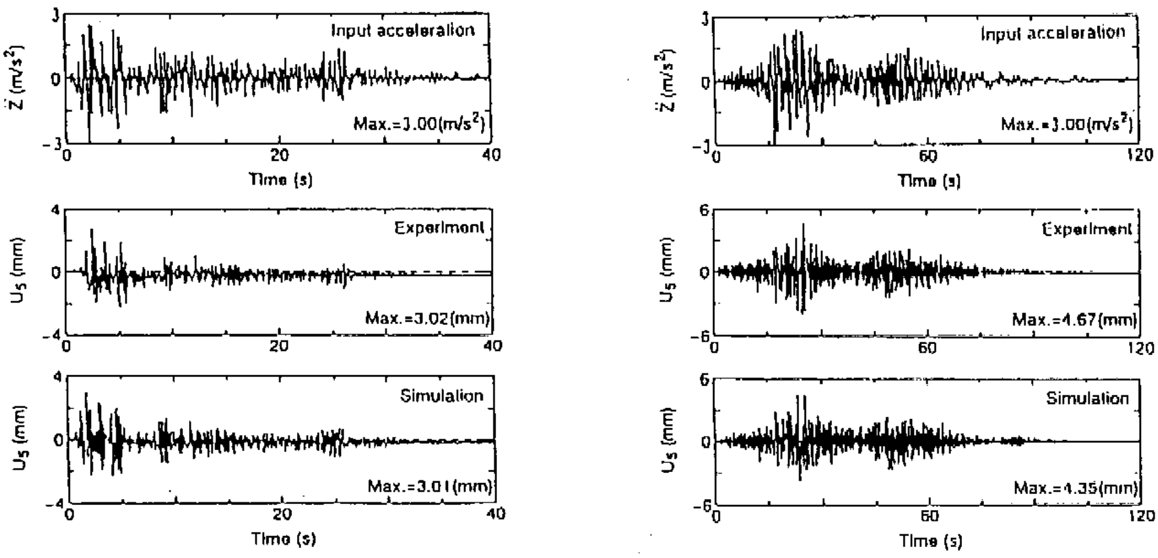
Table 2: Maximum deflection of the pipe at the corner

Unit: mm

Seismic wave			El Centro (1940) NS				Akita (1983) NS			
Max. input acceleration (m/s^2)			0.5	1.0	2.0	3.0	0.5	1.0	2.0	3.0
Without damper		Exp.	1.50	3.09	6.44	8.93	2.55	4.64	9.54	12.69
		Cal.	1.49	2.98	5.97	8.95	2.08	4.15	8.30	12.45
With damper	Aluminum (Φ 3mm)	Exp.	0.24	0.72	1.27	3.02	0.59	1.22	2.69	4.67
		Cal.	0.46	0.93	1.86	3.01	0.64	1.29	2.71	4.35
	Copper (Φ 3mm)	Exp.	0.35	0.60	0.88	1.30	0.47	0.63	0.98	1.35
		Cal.	0.23	0.47	0.93	1.40	0.29	0.57	1.14	1.62

4.3 Shaking Table Test

An experimental model of an L-shaped pipe supported with the elastoplastic damper was also made, and the seismic responses of the pipe were measured making use of an electrohydraulic-type shaking table. The input seismic waves used here were El Centro (1940) NS and Akita (1983) NS normalized to be 0.5 m/s^2, 1.0 m/s^2, 2.0 m/s^2 and 3.0 m/s^2 at the maximum acceleration. The experimental conditions are equal to the numerical conditions of the analytical model given in Table 1. The maximum deflections of the pipe at the



a) El Centro (1940) NS b) Akita (1983) NS

Figure 7: Response deflection waves of the pipe supported by the elastoplastic damper at the corner

corner in the tests both with the damper and without the damper are shown in Table 2. And the experimental and calculated response waves of the pipe at the corner are shown in Fig. 7. The calculated results agree fairly well with the experimental results, and the validity of the calculations is substantiated.

5. FLOOR RESPONSE SPECTRA

Next, consider the response spectra of an apparatus supported by an isolation device consisting of a coil spring and the elastoplastic damper, which is placed at an arbitrary floor in a building, as shown in Fig. 8. The building is a ten storied RC building and is designed by means of the aseismic design method. Natural frequencies of this building through the 1st to the 3rd mode are 1.23 Hz, 3.52 Hz and 5.99 Hz, respectively. It is assumed that mass and damping ratio of the apparatus-isolation system are 200 kg and 2.0 %, and stiffness of the system is varied as the analytical parameter. The apparatus is placed at the top floor in the building. Specifications of the elastoplastic damper are shown in Table 3. The metal rod material of the damper was copper. El Centro (1940) NS, Hachinohe (1968) NS and Tohoku Univ. (1978) NS normalized to be 0.3 m/s at the maximum velocity wave were used as input excitations to the building base.

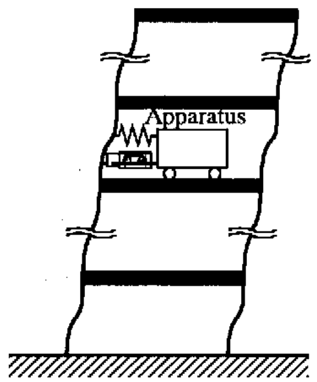


Figure 8: Application of the elastoplastic damper to an apparatus in a building

Table 3: Specifications of the elastoplastic damper

Damper	R (cm)	r (cm)	L (cm)	d (cm)	ke (kN/cm)	Fs (N)
X	2.00	1.60	14.0	0.24	49.5	93.1
Y	2.40	1.75	10.0	0.22	70.1	65.6
Z	3.00	2.00	9.0	0.18	98.0	23.8

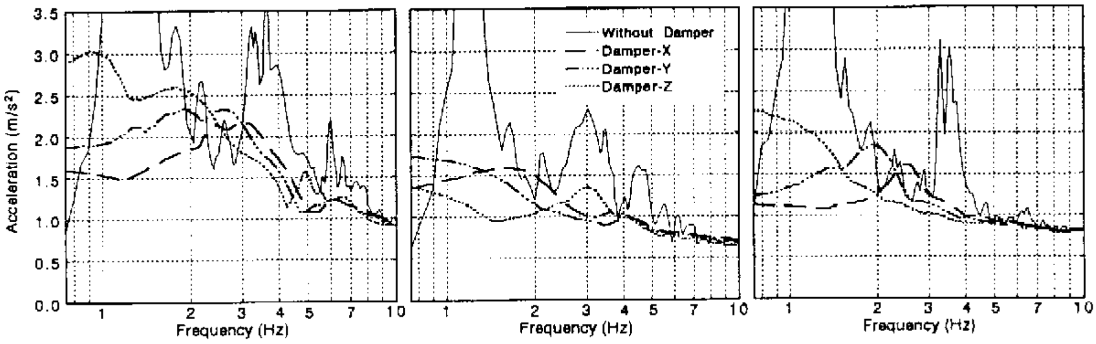
Acceleration and displacement response spactra of the top floor response waves are calculated, and shown in Figs. 9 and 10. It will be seen from those Figures that maximum acceleration and displacement responses of the apparatus drastically decrease by compared with those without the damper within a wide frequency range. Especially, responses of the 1st mode frequency range are less than 1/10 to that of the calculations without the damper.

6. CONCLUSIONS

In this paper, a new type of elastoplastic damper utilizing continuous plastic bending of thin metal rods was made, and its resisting force characteristics and fatigue strength were measured. The seismic responses of an L-shaped pipe supported by the elastoplastic damper were calculated, and the effects of vibration suppression of the damper were discussed. Using the floor response spectra under the seismic excitation, designing indexes for the apparatus on a floor in a building were introduced.

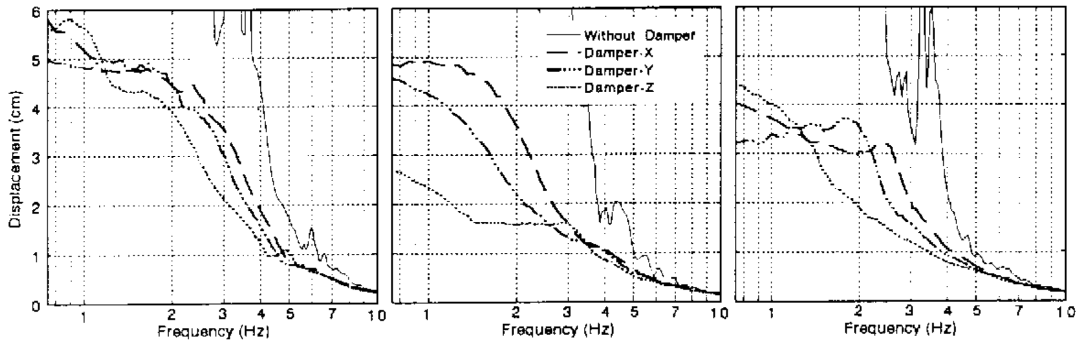
The results may be summarized as follows:

(1) The resisting force characteristics of the trial damper can be assumed to be bi-linear type based on the experimental results of the vibration tests.



a) El Centro (1940) NS b) Hachinohe (1968) NS c) Tohoku Univ. (1978) NS

Figure 9: Acceleration response spactra of the top floor response waves



a) El Centro (1940) NS b) Hachinohe (1968) NS c) Tohoku Univ. (1978) NS

Figure 10: Displacement response spactra of the top floor response waves

(2) The fatigue strength of a rod increases as the diameter or the amplitude of a sinusoidal displacement decreases and a metal rod brakes at the number of cycles more than 1000 regardless of rod materials and the vibration amplitudes.

(3) The most effective resisting force of the damper increases as the maximum input acceleration increases, and the maximum deflection of the L-shaped pipe supported by the elastoplastic damper decreases to between 1/3 and 1/8 that of the calculations without the damper.

(4) This elastoplastic damper is effective in reducing both displacement and acceleration responses of the apparatus placed on a floor of a building under the seismic excitation.

(5) The elastoplastic damper attached to an apparatus in a building is effective within a wide frequency range.

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7. REFERENCES

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