

Development of U-shaped Steel Damper for Seismic Isolation System

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Abstract

Seismic isolation system was widely admitted after Hanshin-Awaji (Kobe) Earthquake in Japan. It has been adopted in important buildings that become a disaster prevention base after earthquakes such as public office buildings and fire stations including a private building a lot. In this paper, the authors easily describe the feature of U-shaped steel damper and the results of experiments to the horizontal property and the velocity and the temperature dependency.

1. Introduction

10 years have passed since the Hanshin-Awaji Earthquake inflicted great damage on Kobe and surrounding areas on January 17, 1995. The earthquake killed no less than 6400 people, and totally destroyed about 180,000 residences (100,000 in terms of the number of buildings) and totally or partially destroyed 500 non-residential buildings. The severity of the damage triggered revisions of various social systems such as the seismic resistance of lifelines and public constructions, disaster prevention planning and emergency rescue systems. Thus, the disaster freshly reminded the country of the importance of always being aware of and prepared for a big earthquake. The renewed awareness and preparation seem to have significant positive effects on the measures taken at the Chuetsu Earthquake in Niigata Prefecture last year.

In the field of building construction, the Hanshin-Awaji Earthquake made people pay more attention to the seismic resistance of buildings, and as a result, technologies to minimize building damage caused by a big earthquake have since been actively studied and developed. Among these technologies, methods for isolating a building from seismic motion, or seismic isolation technology, have attracted attention as the most effective measures to improve the earthquake resistance of a building. The methods have been applied to private housing complexes, socially important buildings such as the official residence of the prime minister, museums, fire stations and government office buildings, disaster-prevention facilities and many other constructions. This is because the current Building Standard

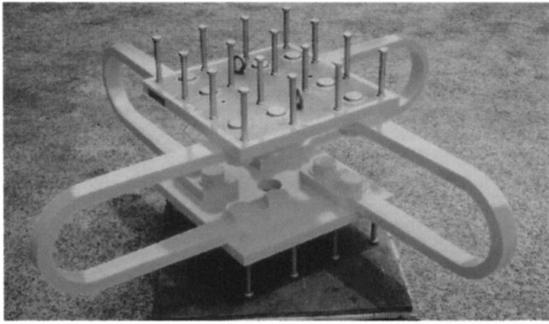
Law assumes that buildings are inevitably damaged by a heavy earthquake; once an earthquake damages a public building, it is disabled from functioning properly. To prevent such an event, the seismic isolation technology that frees buildings from seismic damage is deemed necessary.

Such seismic isolation systems have been applied to about 1000 buildings all over the country. Nippon Steel Corporation has actively cultivated the seismic isolation technology, developed and commercialized seismic isolation dampers as a product in which the long-accumulated technical expertise of the company is fully utilized. One example is a steel-bar damper for seismic isolation that the company launched into the market as a forerunner of the kind: the product has been applied to various buildings such as a computer center building of a group company. The U-shaped steel damper for seismic isolation shown in **Figs. 1** and **2** is another original product of the company making the most of its technical expertise accumulated over years of steel production and utilization.

2. Characteristics of U-shaped Steel Damper

An earthquake shakes buildings in all directions horizontally and vertically, and when seismic isolation dampers are provided, they deform greatly, especially horizontally. Thus, it is necessary for a seismic isolation damper to have a homogeneous damping capacity against horizontal deformation force in all 360 degrees without direction-dependency. Nippon Steel's seismic isolation damper is a product engineered based on long-accumulated technologies in the fields of steel material and working. Its material is used in such a

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4-element damper unit

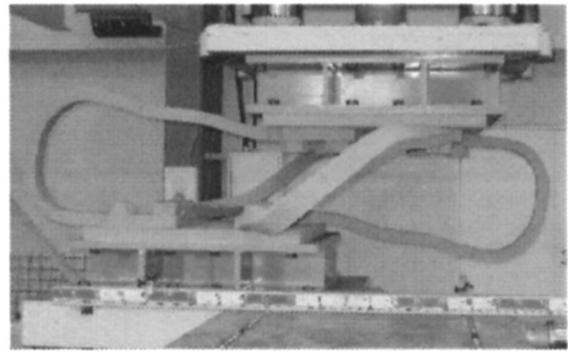
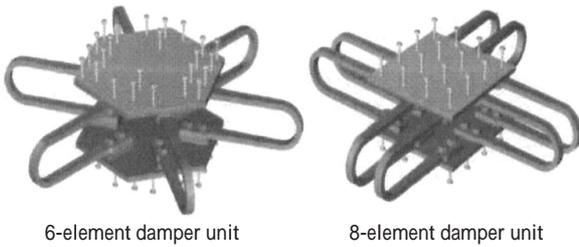


Fig. 3 Deformed shape



6-element damper unit

8-element damper unit

Fig. 1 U-shaped steel damper for seismic isolation system

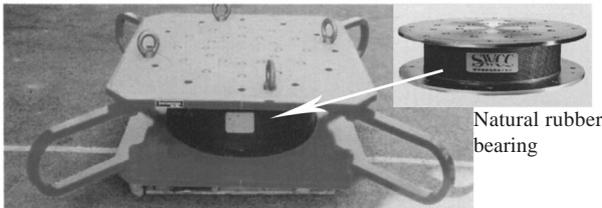


Fig. 2 U-shaped steel damper with natural rubber bearing

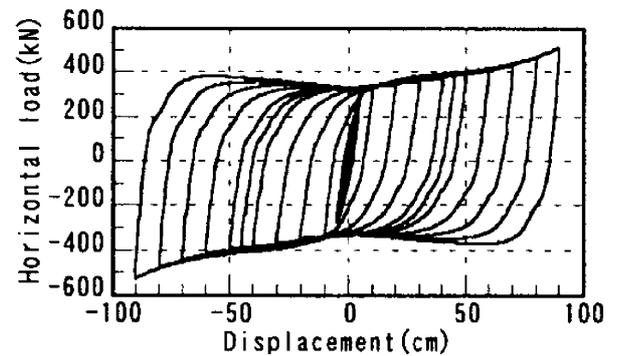


Fig. 4 Hysteresis curve

unique way that it is actively plasticized to absorb seismic energy through plastic hysteresis, like in unbonded braces for building frames, another product of the company to minimize seismic damage of buildings. A seismic isolation damper deforms under a heavy earthquake by as much as 30 cm or more; this means that it is subjected to a very severe fatigue condition wherein strain as large as about 10% repeats at an ultra-low frequency (see **Figs. 3** and **4**). The principal characteristics of Nippon Steel's U-shaped steel damper are as follows:

- (1) U shape (directional independency of horizontal damping performance, excellent fatigue and deformation performance)
A damper element is U-shaped, and its dimensions such as length,

width, thickness and height are determined optimally. As a result of the design, the damper material is plasticized under the horizontal deforming force of an earthquake, which may come in any direction of 360 degrees, and the resultant strain is dispersed all over a damper element without local concentration. The design also minimizes the directional dependency of the stiffness, yield shear force and fatigue properties of a damper element under horizontal force.

- (2) Cold forming (low cost and high quality)

Press forming in cold of the damper element makes mass production possible, reduces production costs and ensures high product quality.

- (3) Product lineup (similar element shapes and variable number of elements for a damper unit to realize low production costs and increase the freedom in design)

U-shaped elements of similar shapes in different sizes compose the lineup of damper units (see **Table 1**). The required deformation

Table 1 Size and properties of U-shaped damper

*: Displacement for 5 cycles to failure

Model	Size					Properties using four U-dampers				
	Length (mm)	Height (mm)	Thickness (mm)	Width (mm)		Yield shear force (kN)	Horizontal 1st stiffness (kN/m)	Horizontal 2nd stiffness (kN/m)	Horizontal elastic limit displacement (mm)	Horizontal limit displacement*
UD40	610	231	28	60	112	5920	100	19	550	
UD45	785	297	36	77	184	7600	128	24	650	
UD50	872	330	40	85	232	8320	144	28	750	
UD55	981	371	45	96	304	9600	160	32	850	
UD60	1199	453	55	118	432	11600	196	37	1000	

and fatigue properties of a damper unit defined in the building design are met by adequately selecting the most suitable size of damper elements. The number of damper elements per unit is determined according to the required yield shear force and the number of damper units defined in the building design (see Fig. 1). Thus, the product lineup allows wide freedom of design for the building. In competition with similar products, Nippon Steel has also developed and commercialized composite damper units in which the U-shaped damper elements are combined with a laminated rubber bearing (see Fig. 2).

3. Performance Tests of U-shaped Steel Damper

The authors conducted various tests to confirm the performance of the U-shaped damper. The principal performance items of the damper element are explained hereafter based on the results of two kinds of tests: one regarding the dependency of performance on the direction of horizontal seismic force (load), and the other regarding the dependency on temperature and the velocity of loading.

3.1 Tests of dependency on horizontal direction

3.1.1 Test outline

For the purpose of confirming the effect of the direction of force on the performance of a damper element, one-element specimens of UD40 were subjected to horizontal loads at angles from 0° (in-plane) to 90° (out-of-plane) with respect to the axis of the damper element, and the mechanical and fatigue performance of the specimens under loads at different angles were compared. The loads were imposed statically at a velocity of 10 mm/s. The material of the specimens was equivalent to JIS SM490, and was used after cold bending and heat treatment.

3.1.2 Test results

Figs. 5 to 7 show the test results under static, increasing loads in 0° (in-plane), 45° and 90° (out-of-plane) directions, respectively. The specimens exhibited stable hysteresis characteristics under horizontal loads in different directions. Figs. 8 and 9 show the relationships between yield shear force, elastic limit displacement and first and second stiffness at different loading angles. Yield shear force changed from 2.8 tf at a loading angle of 90° (out-of-plane) to 3.0 tf at a loading angle of 0° (in-plane), demonstrating only a small difference depending on the loading angle. Yield shear force and first stiffness decreased with increasing loading angle, and in contrast, elastic limit displacement and second stiffness increased.

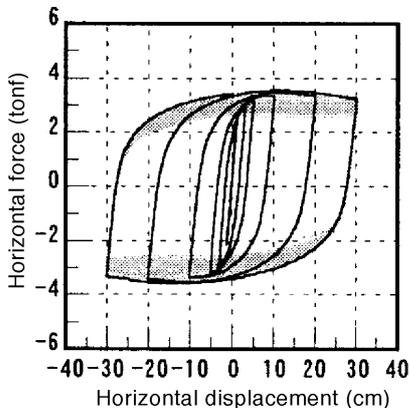


Fig. 5 Hysteresis curve (In-plane direction)

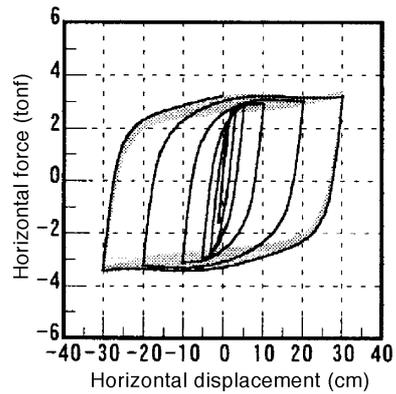


Fig. 6 Hysteresis curve (45deg. direction)

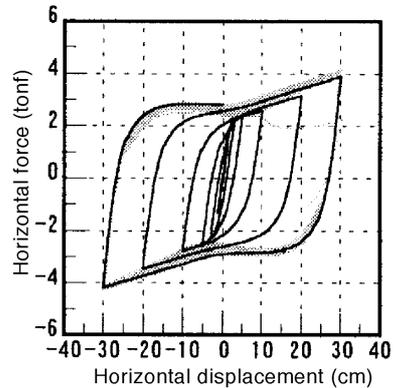


Fig. 7 Hysteresis curve (Out-of-plane direction)

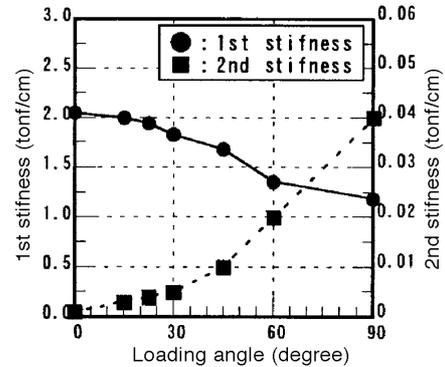


Fig. 8 Effect of loading angle on stiffness

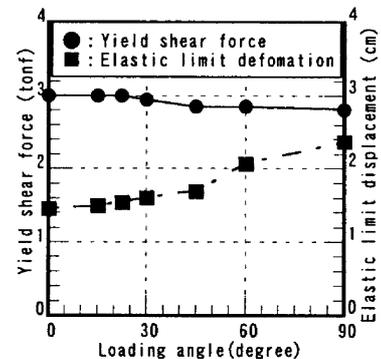


Fig. 9 Effect of loading angle on yield shear force and elastic limit

load of an amplitude of ± 30 cm was equal to that measured in the tests. The results of loading tests under cyclic, constant displacement at loading angles of 0, 45 and 90° are also shown in Figs. 5 to 7 in gray. The specimens exhibited stable hysteresis characteristics under the cyclic loads at different loading angles, as well.

Fig. 10 shows positions of the failure resulting from cyclic loads at different loading angles. The position of failure changed depending on the loading angle: specimens failed at position D under a cyclic load at an amplitude of ± 30 cm at a loading angle of 0° (in-plane), at position A under the same load at a loading angle of 45°, and at position E under the same load at a loading angle of 90° (out-of-plane). When there is an earthquake, a damper element undergoes deforming force in all 360° directions, and in such a condition, the energy is absorbed not through strain concentration at a certain portion of the element but through its dispersion over the entire element. What is more, under cyclic loads at a loading angle of 0° (in-plane), the specimens failed at different positions at amplitudes of ± 30 and ± 50 cm. The reason why the fatigue properties deteriorated less under in-plane loads of amplitudes larger than ± 30 cm than under loads in the other directions is that the damper material was plasticized in an entire element.

3.1.3 Fatigue properties

Fig. 11 shows the relationship between the number of load cycles to failure (Nf) and the amplitude of the load (δt). The number of cycles to failure is small under in-plane (0°) loads up to an amplitude of approximately ± 30 cm, and when the amplitude exceeded ± 30 cm, the specimens failed quicker under loads in the 45° direction.

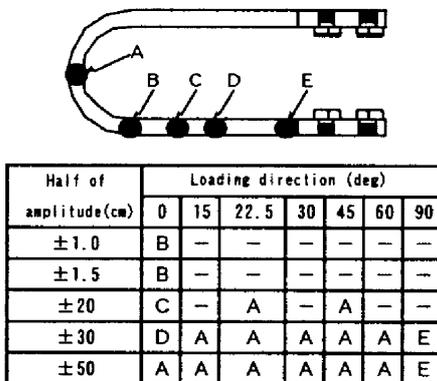


Fig.10 Failure patterns of specimen

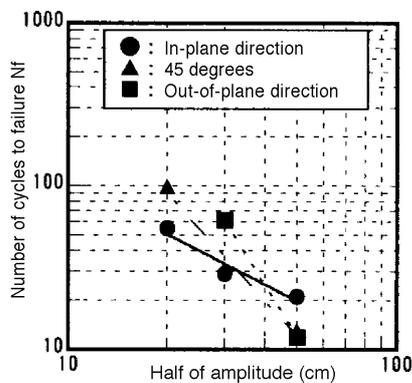


Fig. 11 Fatigue property

3.1.4 Summary

All the specimens exhibited stable hysteresis characteristics under loads at different loading angles, and the directional dependency of strength and stiffness was confirmed to be small.

3.2 Tests of dependency on load velocity and temperature of use

3.2.1 Test outline

Fig. 12 shows the damper element specimen used for the test and the test equipment. The specimens were UD40 (28 mm thick) and its scaled models reduced to 1/3.11 (0.322); steel plates 9 mm in thickness of SN 490B under JIS G 3136 after bending work and heat treatment were used as the material of the reduced-scale specimens. The mechanical properties of the specimens were as follows: upper yield point was 341 N/mm², tensile strength was 503 N/mm², and the Charpy impact value at 20°C was 268 J. The specimen was fixed at the upper and lower ends to the loading equipment of the tester with bolts, and horizontal cyclic deforming force under sinusoidal displacement control was applied to the specimen using a 500-kN actuator until it failed. The space around the tester was enclosed with foamed polystyrene, and the specimen temperature was controlled using a jet heater for heating and liquid nitrogen for cooling. Table 2 shows the test conditions. The loads were applied in the 0 (in-plane), 45 and 90° (out-of-plane) directions.

3.2.2 Test results

(1) Comparison between full-scale and reduced-scale specimens

Table 3 compares the test results of the full-scale and reduced-scale specimens. It has to be noted here that the figures of the reduced-scale specimens are those converted into full scale. The val-

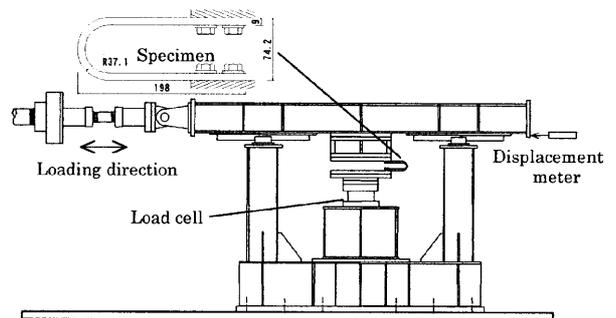


Fig. 12 Elevation view of test set-up

Table 2 Loading pattern

Temperature (°C)	Loading direction	Specimen No.	Period (s)	Amplitude (cm)	Max. velocity (cm/s)	
					1/3 scaled	Full scale (× 3.11)
20	In-plane	1	Static	6.4	0.7	2.2
		2	2.8	6.4	14.3	44.4
		3	1.7	6.4	23.8	73.9
		4	1.1	6.4	35.7	111.1
	45 degrees	5	Static	6.4	0.7	2.2
		6	1.7	6.4	23.8	73.9
	Out-of-plane	7	Static	6.4	0.7	2.2
		8	1.7	6.4	23.8	73.9
40	In-plane	9	1.7	6.4	238	73.9
-10		10	1.7	6.4	23.8	73.9
-30		11	1.7	6.4	23.8	73.9
-50		12	1.7	6.4	23.8	73.9

Table 3 Comparisons between 1/3-scale and full-scale specimens

Specimen No.	Loading direction	Amplitude (cm)	Yield shear force (kN)	1st stiffness (kN/cm)	1 cycle energy (kN/cm)	Cycle dependency W1 (50)/W1 (3)	Number of cycles to failure
1	In-plane	20	30	20	2236	0.80	62
Full scale			29	20	2113	0.78	55
9	45 degrees		28	16	2015	0.83	111
Full scale			28	16	1875	0.82	99
12	Out-of-plane		28	11	1752	0.92	181
Full scale		27	12	1688	-	-	

ues of amplitude, yield shear force and first stiffness of the bilinear model for analysis were approximated in such a way that the absorbed energy in the cycle of the third loop at the maximum amplitude calculated by the model was equivalent to the same measured in the tests. As a result, the converted values of the first stiffness and yield shear force calculated by the bilinear model corresponded favorably with actual test values. The number of cycles to failure of reduced-scale specimens agreed reasonably well with those of the full-scale specimens, except that the figures of the reduced-scale specimens were larger by about 10%. The results showed that although the reduced-scale specimens were small, only 9 mm in thickness, their hysteresis characteristics agreed well with those of real-size dampers.

(2) Dependency on load velocity

The authors compared the bilinear model figures of yield shear force and first stiffness, the absorbed energy per 1-cycle load and the number of cycles to failure under the loads of an amplitude of ± 6.4 cm at loading angles of 0° (in-plane), 45° and 90° (out-of-plane), setting the maximum velocity at 0.7 (static), 14.3, 23.8 and 35.7 cm/s. **Figs. 13 to 15** show the ratios of the measured values relative to those (plotted at 1.0) under the static load (0.7 cm/s) at each of the loading angles, and **Fig. 16** shows the relationship between the number of cycles to failure and the maximum velocity of the load.

The yield shear force and 1-cycle absorbed energy increased with increasing strain velocity: the yield shear force under the maximum velocity of 35.7 cm/s was larger by 7% than that under the static load (0.7 cm/s), and the 1-cycle absorbed energy by 6%. On the other hand, the number of cycles to failure decreased with increasing strain velocity: at the loading angle of 0° (in-plane), at which the fatigue was the largest at the amplitude of ± 6.4 cm, the number of cycles to failure under the maximum load velocity of 35.7 cm/s fell from that under the static load (0.7 cm/s) by about 20%. The influence of strain velocity on first stiffness was small: first stiffness increased by only 2 to 3% with increasing strain velocity.

(3) Dependency on temperature

Setting the angle of loading at 0° (in-plane), the amplitude at ± 6.4 cm and the maximum load velocity at 23.8 cm/s and changing the specimen temperature to 40, 20, -10, -30 and -50°C, the authors compared the yield shear force calculated by the bilinear model and 1-cycle absorbed energy. **Figs. 17 and 18** show the ratios of the measured values relative to those at 20°C, which are plotted at 1.0.

Yield shear force and 1-cycle absorbed energy increased as the temperature fell: their values changed from -3% at 40°C to +10% at -50°C in relation to the respective values at 20°C. As far as seismic isolation dampers are actually used inside a temperature range of 20 to -10°C, the increases in yield shear force and 1-cycle absorbed energy will be +3% or so.

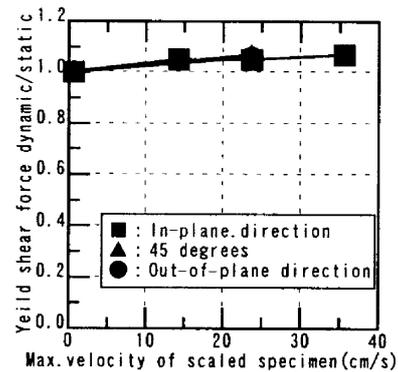


Fig. 13 Yield shear force vs. max. velocity

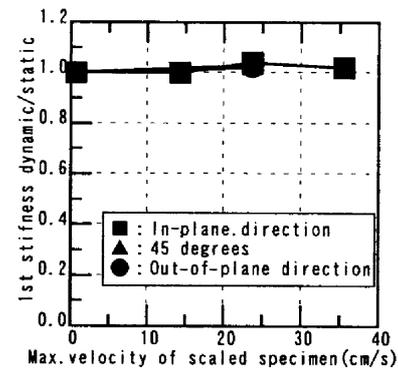


Fig. 14 1st stiffness vs. max. velocity

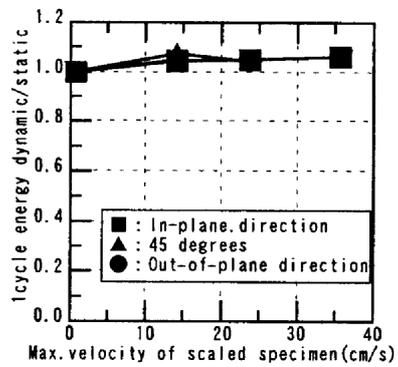


Fig. 15 1 cycle energy vs. max. velocity

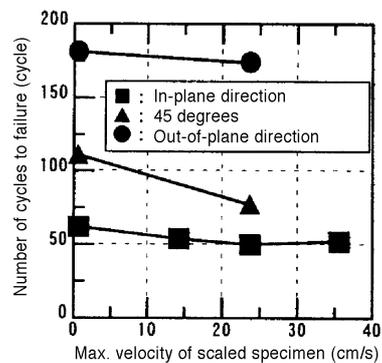


Fig. 16 Number of cycles to failure vs. max. velocity

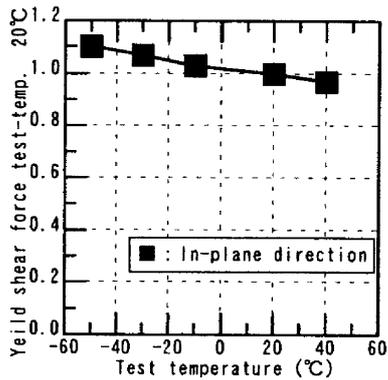


Fig. 17 Yield shear force vs. test temperature

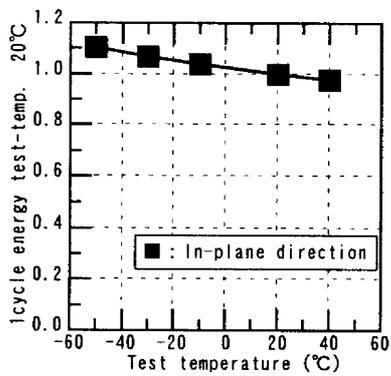


Fig. 18 1 cycle energy vs. test temperature

3.2.3 Summary

- (1) The specimens exhibited stable hysteresis characteristics under different strain velocities and temperatures. Under sinusoidal, cyclic loads having a natural period of 3 s, an amplitude of ± 35 cm and a maximum strain velocity of 73 cm/s, the yield shear force of a UD55 damper (45 mm thick) will increase by 3% with respect to that under a static load.
- (2) The change in the hysteresis characteristics at different temperatures will be +3% or so, as far as the temperature range is from 20 to -10°C .
- (3) Through tests using reduced-scale specimens, the strain velocity- and temperature-dependency of the damper behavior were confirmed to be predictable, as far as strain velocity and temperature fluctuate within the respective ranges discussed herein.

4. Closing

The authors intend to further promote the seismic isolation technology, which is one of the best countermeasures against seismic damage presently available, and increase the number of buildings resistant to earthquakes.

Acknowledgement

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References

- 1) Suzuki, K., Watanabe, A. et al.: Experimental Study of U-shaped Steel Damper. Summary of Technical Papers of Annual Meeting, Architectural Institute of Japan, B-2. 1999, 2000