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Development of Earthquake-Resistant, Vibration Control, and Base Isolation Technology for Building Structures

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Abstract:

This paper outlines recent developments concerning earthquake resistance, base isolation ,and vibration control of structures at the Building Construction Division of Nippon Steel. The energy absorption requirements of steels are introduced for buckle-restraining unbonded braces, steel plate shear panels, and steel bar dampers. New directions in structural steels are presented, as new seismic design ideas that are appearing in the construction field. The Great Hanshin Earthquake of January 17, 1995 enhanced people's interest in the safety of buildings. Against this background, this research area will receive ever increasing attention. Steel engineers will have to work together with structural engineers to design earthquake-resistant buildings. A friction damper made of advanced ceramic material and a tuned liquid damper (TLD) are also described.

1. Introduction

Architects and engineers in earthquake-prone Japan face the huge challenge of how to design and build structures that can withstand the forces of a major earthquake, which could strike at any time. Much effort has been made to date to develop tough and stable earthquake-resistant structural elements. In recent years, such structural elements have been put to increasingly positive use as energy absorbers. For example, some elements are designed to plasticize on the onset of vibration to absorb energy and to efficiently control vibration, or energy absorption is concentrated on particular elements to simplify the earthquake-resistant mechanism and to ensure the soundness of vertical support members. The Great Hanshin Earthquake heightened people's interest in structural safety. Against this background, structural safety is expected to be studied in greater earnest than in the past. In this paper, the buckle-restraining unbonded brace, steel plate shear panel and other earthquake-related technologies developed by Nippon Steel are introduced, and new directions in structural steels are described.

The buckle-restraining unbonded brace was developed as an earthquake-resistant structural element with excellent toughness. The core contains steel pipe and mortar to prevent buckling and to provide stable restoration characteristics for both compression and tension. The experimentation of full-size, large-capacity unbonded braces was carried out to confirm their restoration characteristics and strain distribution, the effect of secondary bending moment on them, and steel pipe safety. Unbonded braces made of ultrahigh-strength steel (WT780), ultralow-yield point steel (LYP100), are studied as new types of earthquake-resistant

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structural elements.

The elastic-plastic hysteresis-type steel plate shear panel is made of low-yield point steel, and was developed as an element with high toughness and capacity to maintain stability during large deformation. The vibration control effect of the steel plate shear panel when caused to yield early (at about a half of the design load level) is also described.

To judge the safety of earthquake isolation steel dampers during a massive earthquake, their fatigue curves are obtained by fatigue testing full-size models. The method for evaluating their cumulative fatigue damage is verified by failure experimentation with random waves.

The results of comparative studies conduced on various metallic materials as components of energy absorption systems are also introduced. One approach to evaluate the energy absorption capacity of various types of metals is presented, and future prospects are described.

As applications of new materials, a ceramic friction material with small speed dependence and excellent durability, and a friction damper made from ceramic friction material are introduced.

Tuned liquid dampers (TLDs) developed for controlling the vibration of towers and similar structures, and their application benefits are also described.

2. Buckle-Restraining Unbonded Brace

Braces are well known as effective earthquake-resistant structural elements and are widely used in low- to high-rise buildings. When compressed, however, braces buckle and rapidly lose yield strength. This is a serious shortcoming of braces as members that must absorb earthquake energy in their plastic region. The buckle-restraining unbonded brace with a steel pipe and mortar core that restrains buckling was developed, and has been used in many buildings to date (see **Figs. 1** and **2**).

When the buckle-restraining unbonded braces were put into practical use, their stability restoring characteristics were verified by a variety of experiments. With their original sizes, proportions, and materials, unbonded braces cannot be used in some larger structures constructed in recent years. The unbonded braces have found increasing use not only as passive earthquake-resistant structural elements, but also as tools for positively controlling such building vibration properties as natural period, damping factor, ductility factor, modulus of rigidity, and modulus of eccentricity. Against this background, large-capacity unbonded braces were investigated to understand their behavior and to study the effect of secondary bending moment and the buckling safety factor of steel pipe (see **Table 1**).

Also studied was the possibility of a new type of unbonded

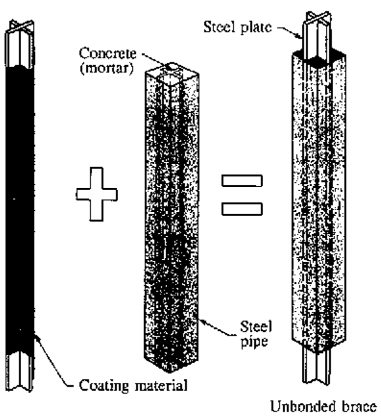


Fig. 1 Construction of buckling-restrained unbonded brace

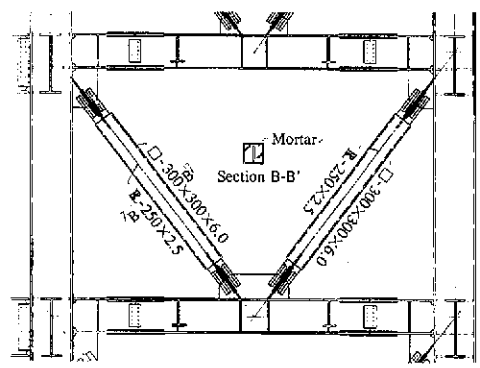


Fig. 2 Example of design

Table 1 List of specimens

	Specimen	Core			Steel pipe size	Eccentricity (mm)	Coating material thickness (mm)
		Material	Type	Size			
Basic model	400−36	SS400	−	36×250	□-300×300×6	None	2.0
	400+28	↑	+	28×250	↑	↑	↑
Thin-wall steel pipe model	400−36T16	↑	−	36×250	□-300×300×1.6	↑	↑
	400+28T16	↑	+	28×250	↑	↑	↑
Coating material thickness change model	400−36C05	↑	−	36×250	□-300×300×6	↑	0.5
	400−36C40	↑	−	36×250	↑	↑	4.0
Dissimilar steel model	780−19	WT780	−	19×231	↑	↑	2.0
	100−19	LYP100	−	19×250	↑	↑	↑
	800+19	Note	+	19×250	↑	↑	↑
Eccentric model	400−36E30	SS400	−	36×250	↑	30	↑
	400−36E80	↑	−	36×250	↑	80	↑
	400+28E20	↑	+	28×250	↑	20	↑
	400+28E50	↑	+	28×250	↑	50	↑
	400+A28E50	↑	+	28×250	↑	50	↑

Note: Core for specimen 880+19 is cross of WT780 and LYP100.

brace with a core made from the combination of high-strength steel (WT780) and ultralow-yield point steel (LYP100). The new unbonded brace was studied on a 1,000-ton structure testing machine at the Ministry of Construction's Building Research Institute (see **Photo 1**).

When the specimens were subjected to gradually increasing loading to achieve an axial deformation of ±50 mm (axial strain of 1/100), they didn't buckle and provided stable hysteresis characteristics for both tension and compression as shown in **Fig. 3**. Their strain distribution was also uniform.

It was confirmed that if the buckling safety factor of the steel pipe is set at 1.0 with respect to the core, the steel pipe can perform as fully as expected, and that the change in the coating material thickness has little or no effect on the hysteresis characteristics of the unbonded brace. As far as the secondary bending moment of the unbonded brace is concerned, it was also confirmed experimentally and analytically that the unbonded brace can retain its hysteresis characteristics if its length between the joints is at least about a half of its core distance.

When their core is made from the high-strength steel (WT780), ultralow-yield point steel (LYP100), or both, the unbonded braces all exhibit stable hysteresis characteristics up to an axial deformation of 50 mm (axial strain of 1/100). When the core is made from the combination of the high-strength steel (WT780) and ultralow-yield point steel (LYP100), the increase in the energy absorption capacity due to the ultralow-yield point steel is clearly manifested. This confirmed the feasibility of a new type of unbonded brace featuring both earthquake-resistance and vibration control (see **Figs. 4** to **6**).

The buckle-restraining unbonded braces are earthquake-resistant and vibration controlling structural elements designed to absorb energy. They are also suitable for applications in low- to high-rise buildings, and for reinforcing existing buildings against earthquakes. The development of unbonded braces will continue to be carried out to meet a variety of needs.

In December 1991, the buckle-restraining unbonded braces were generally approved by the Building Center of Japan as earthquake-resistant structural members.

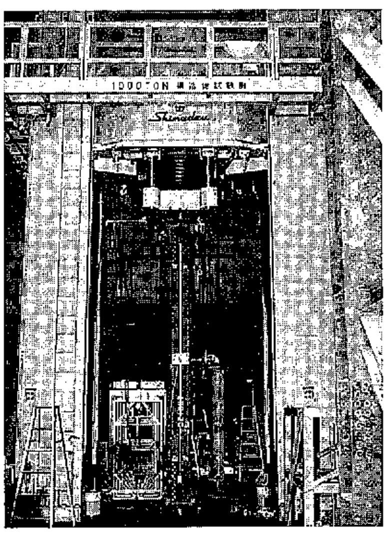


Photo 1 General view of specimen

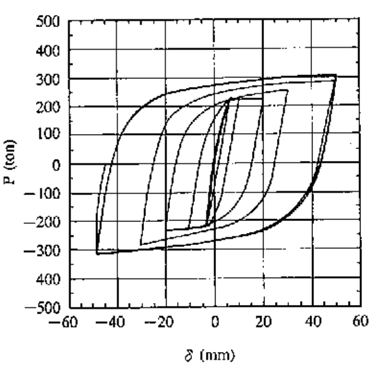


Fig. 3 Load versus axial deformation

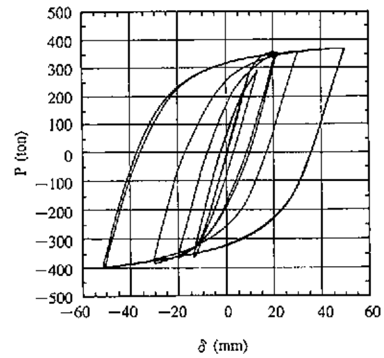


Fig. 4 Load versus axial deformation (WT780)

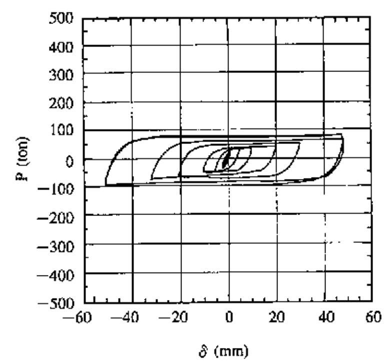


Fig. 5 Load versus axial deformation (LYP100)

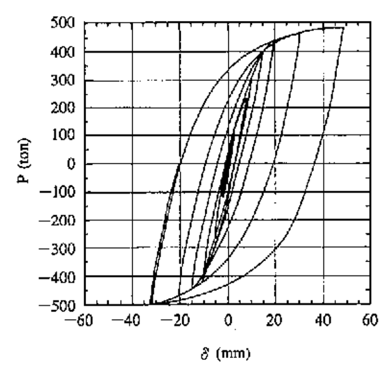


Fig. 6 Load versus axial deformation (WT780 + LYP100)

3. Shear Panels (Steel Plate Shear Panels of Elastic-Plastic Hysteresis Type)

Vibration control mechanisms that depend on the hysteretic vibration control devices must have greater plastic deformation than yield deformation of an earthquake vibration control device if they are to demonstrate their effectiveness. They are effective against large earthquakes involving large deformation, but are not expected to control vibration during small and medium earthquakes. By considering the characteristics and limitations of various vibration control devices, shear panels with a low-yield point steel plate panel to control seismic vibration were developed as a vibration control mechanism effective against small to large earthquakes. Their features follow:

(1) Shear panels increase the initial stiffness of buildings and reduce the deformation of buildings in small and medium earthquakes.
(2) In large earthquakes, shear panels function as hysteretic dampers, reducing the response value of buildings.
(3) Shear panels carry the horizontal forces of earthquakes and wind.
(4) The vibration criteria for starting the hysteretic damping of the shear panel can be freely designed by setting its shear yielding load.

Fig. 7 shows an example of a building with a steel plate shear panel (made of the low-yield point steel BT-LYP100) installed in the span of each layer. The steel plate shear panels are shear yielding panels braced to provide high horizontal stiffness. They are installed to receive pure shear under earthquake load. Their low-yield point is utilized for the hysteretic dissipation of earthquake energy.

In this example, the steel plate shear panels are used in a 30-story building. They are made of low-yield point steel with high toughness so that they yield at an earthquake load about a half of the primary earthquake-resistant design level and do not degrade in energy dissipation capacity until they reach the secondary earthquake-resistant design level. A preliminary study found that the installation of the steel plate shear panels can increase the damping factor of the building by about 1% and reduce the response of the building to steady-state vibration and random vibration by about 15% and about 5%, respectively.

Low-yield point steel plate shear panels were experimentally studied to see if they would successfully function as energy dissipation parts in the structures shown in **Figs. 7** and **8**. Some of the experimental results are introduced below.

Shear panels made of 6-mm thick low-yield point steel (BT-LYP100) were removed and statically and cyclically loaded in the panel shapes shown in **Table 2**. The specimen parameters are the panel width-to-thickness ratio, rib stiffness, and panel yielding axial force ratio. The shape of the panel specimen that had one side stiffened vertically and horizontally is shown in **Fig. 9**. The condition of the panel after loading is shown in

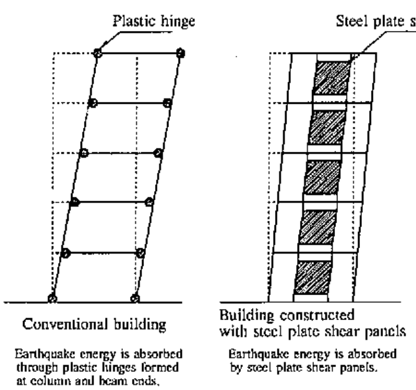


Fig. 7 Comparison of conventional building and building using steel plate shear panels as energy absorpers

Table 2 Types and load conditions of steel plate shear panels

Material	Type of specimen / Load condition	Without stiffener	Both sides vertically stiffened	Both sides vertically and horizontally stiffened	One side vertically and horizontally stiffened	One side vertically and horizontally stiffened
Low-yield point steel	Static gradually increasing cyclic load (no axial force)	○	○	○	○ ○ (Rib PL-12)	○
	Static gradually increasing cyclic load (with axial force)	○ (30%)	○ (30%)	○ (45%)	○, ○ (45%) (45%)	○ (45%)

Unless otherwise specified, stiffening ribs are PL-6.

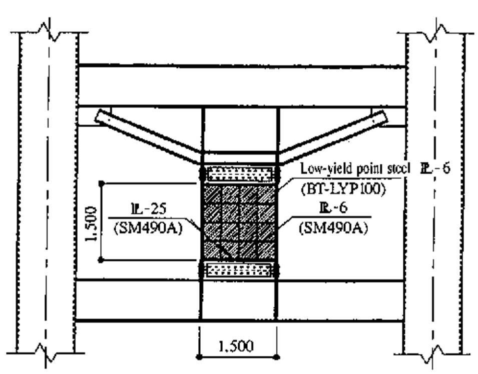


Fig. 8 Detail of steel plate shear panel

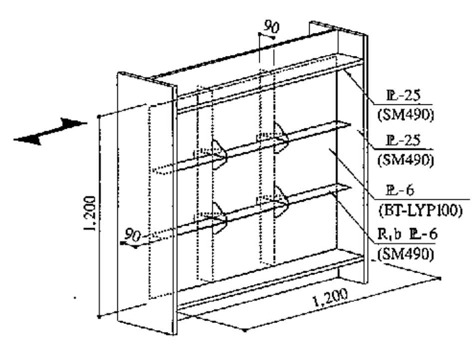


Fig. 9 Steel plate shear panel with one side vertically and horizontally stiffened (vertically and horizontally divided into three parts each and rib thickness of 6 mm). Static gradually increasing cyclic load (no axial force)

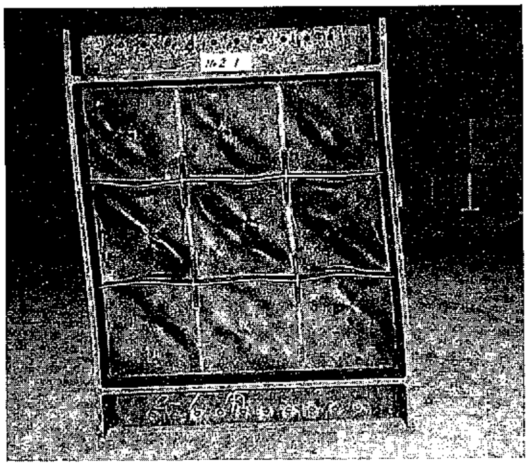


Photo 2 View of steel plate shear panel after loading

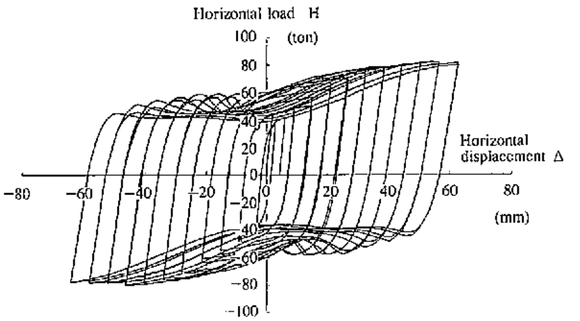


Fig. 10 Shear force versus horizontal displacement relationship obtained from test

Photo 2, and the experimental results of the specimen are shown in **Fig. 10**. The following can be understood from the experimental results:

(1) The energy dissipation capacity of the steel plate shear panel under cyclic deformation is extremely stable, and full hysteretic damping can be expected in a wide displacement range from small to large displacement values.

(2) The degradation of hysteresis is promoted by the plate buckling, increase in out-of-plane deflection resulting from subsequent cyclic loading, and cracking induced by excessive out-of-plane deflection. The plate buckling itself does not directly lead to the immediate degradation in energy dissipation capacity. The marked decline in energy dissipation capacity requires severalfold more cycles after the onset of plate buckling.

(3) If such rib stiffness is established that low-yield point steel plate panels do not totally buckle when they carry a large horizontal force, a very stable hysteresis loop without yield strength degradation can be expected.

Steel plate shear panels with a large energy dissipation capacity can be installed in a building to concentrate earthquake energy and damage on them. The steel plate shear panels protect the main structure of the building from earthquake damage and allow the building to continue to be used after earthquakes. These panels can withstand a few earthquakes of the intensity of the 1923 Great Kanto Earthquake that had a magnitude of 7.9. If the panels are severely plasiticized, the panels alone can be replaced.

4. Earthquake Vibration Isolation Steel Dampers

Earthquake vibration-isolated building construction uses laminated rubber isolators of low horizontal stiffness to isolate the entire building from the surrounding ground and to prevent the transmission of the earthquake force to the building, and it also uses dampers to absorb earthquake energy (see **Fig. 11**). Nippon

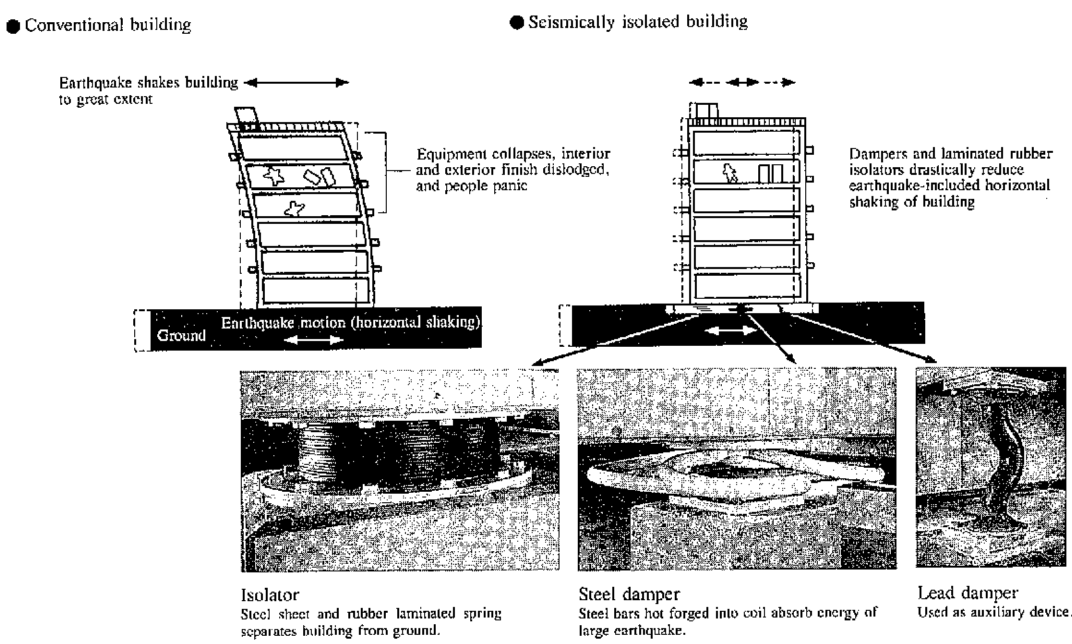


Fig. 11 Seismically isolated building construction

Steel commercialized a steel damper made from four round steel bars shaped like petals. The steel damper has already been explained elsewhere[1] and therefore is not described in depth here. Described here are the methods for testing the cyclic performance of steel dampers and evaluating the cumulative fatigue damage of steel dampers.

The steel damper converts vibratory energy into thermal energy by the plasticization of the steel, thereby suppressing the horizontal vibration of the building. As the damper increases in efficiency, it makes more effective use of plastic strain, and its durability or plastic fatigue is highlighted accordingly. It is necessary to judge whether or not the damper should be replaced when subjected to a very strong earthquake.

When designing a damper, it is also necessary to select a rational shape and material after understanding the performance of the building to be supported by the damper and the performance required of the damper.

Against this background, Nippon Steel fatigue tested full-size dampers jointly with Okumura Corporation and obtained fatigue curves. Nippon Steel also fracture tested full-size steel dampers with random waves, verifying that Miner's rule practically applies to steel dampers.

The specimens were steel dampers made of 70 mm diameter steel bars. The single-loop type was dynamically tested under cyclic loading in two directions, and the four-loop type was tested by gradually increasing the load and large deformation (see **Table 3**). The steel bars were made of chromium-molybdenum steel (SCM415) and annealed after bending (see **Table 4**). The specimens were tested on a compression shear testing machine at Okumura Corporation's Tsukuba Technical Research Institute (see **Photo 3**).

The dynamic cyclic loading test results are shown as "amplitude to number of cycles to failure, N_f" and "strain-N_f," together with regression curves and equations in **Fig. 12**. A certain relationship is apparent between the maximum strain and N_f.

Random waves were produced by the response analysis of a building seismically isolated with steel dampers. The steel dampers were cyclically excited with the random waves, and the number of the random waves the steel dampers withstood before their failure was counted. The steel dampers were found to withstand 26 earthquake waves with a velocity of 50 kines as recorded in the 1968 Hachinohe earthquake in northern Japan. When calculated from the strain, the cumulative fatigue damage rate (Dk) of the steel dampers falls within 0.721 to 0.819. This means that Miner's rule holds true for the steel dampers. This finding makes it possible to obtain the displacement of a building in a large earthquake by response analysis, to calculate the cumulative fatigue damage rate of the steel dampers to be used for the building, and to verify the durability of the steel dampers and the safety of the building in a large earthquake (see **Table 5**).

Table 3 Test items and number of specimens

Test item	Shape of specimens	Number of steel bars	Number of specimens
(a) Static monotonically increasing loading test	70 ϕtype	4 1	2 [2]
(b) Large-deformation loading test		4	(1)
(c) Constant-displacement dynamic cyclic loading test		4	(1)
(d) Constant-displacement dynamic cyclic loading test		1	14
(e) Response wave loading test		1	5

Specimens enclosed in brackets were also used in test (d), and specimens enclosed in brackets were also used in test (a).

Table 4 Mechanical properties of steel bars

Item	Test result
Yield point (kgf/mm²)	33.3–34.7
Elongation (%)	32.5–35.9
Hardness HB	141–145

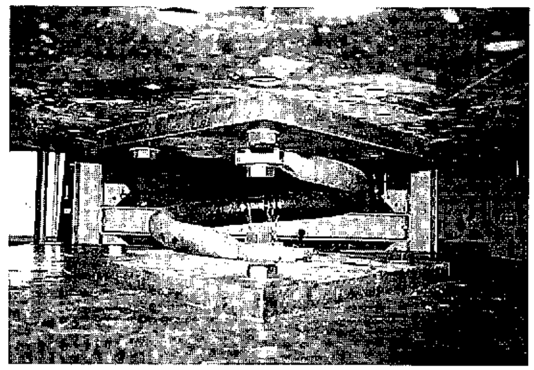


Photo 3 Specimen

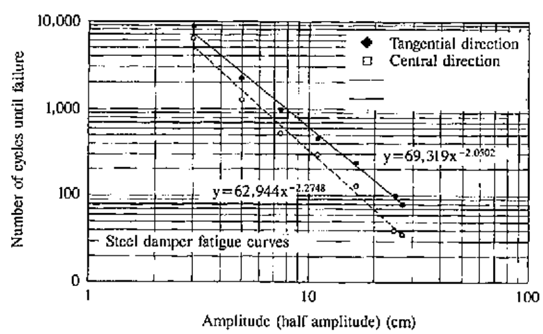
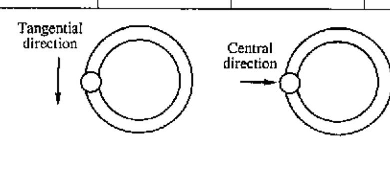


Fig. 12 Amplitude and number of cycles until failure

Table 5 Number of waves until failure and cumulative fatigue damage rate

Direction	Wave	Number until waves to failure	Cumulative fatigue damage rate Displacement	Strain
Tangential	HACHI 25	238.1	0.967	0.733
	HACHI 50	66.3	1.108	0.798
	EL CE 50	67.1	0.944	—
Central	HACHI 25	140.7	0.870	0.721
	HACHI 50	26.2	0.827	0.819



5. Study of Energy Absorption Systems

Structural elements have been traditionally designed by considering the amount of energy they hysteretically absorb as they become plastic. In many cases, the degree by which each structural member contributes to absorbing earthquake energy is not always clear. It has been proposed that structural members other than vertical load carrying members, such as columns and beams, should be designed to absorb energy from earthquakes and typhoons.

Steel and other metals are durable, stable, strong, and relatively free from the effects of temperature and deformation rate, but have many properties to be clarified from a energy absorption standpoint. Among such properties are the plastic deformation capacity, cumulative plastic deformation capacity, relationship between displacement amplitude and number of cycles before failure under cyclic loading, effect of strain hardening, cumulative energy absorption capacity, and required service performance properties.

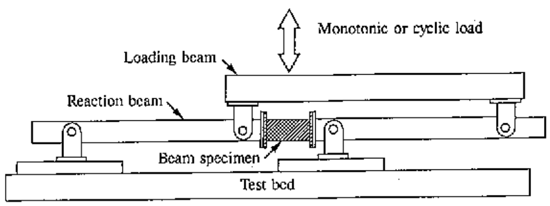


Fig. 13 Loading apparatus

Against this background, Nippon Steel conducted a joint study with the Ministry of Construction's Building Research Institute on the utilizability of various metals as energy absorption members. To study the feasibility of various metals as energy absorption devices, short beams (H-250 × 125 × 6 × 9) with an aspect ratio (length/depth ratio) of 1, 2, or 4 were shear tested (see **Fig. 13** and **Photo 4**). The typical test results of specimens by gradually increasing loading and cyclic loading are shown in **Fig. 14**. When tested under cyclic loading, the specimens with the aspect ratio of 4 absorbed a larger cumulative amount of energy than those with the aspect ratio of 1 or 2. This is probably the result of yield strength deterioration stemming from the flexural yielding of the flange.

The above-mentioned short beams were assembled as energy absorption devices in a portal frame and load tested (see **Photo 5**). The webs were made of LYP235, LYP100, or LYP100 in combination with SS400, and the aspect ratio was 2 (see **Fig. 15**). Each specimen exhibited spindle-shaped hysteresis loops rich in energy absorption capacity. The real yield load of each specimen can be calculated as the sum of the yield load of the portal frame and the shear yield load of the energy absorption device.

Various attempts have been made to evaluate the energy absorption capacity of steels. The energy absorption capacity data

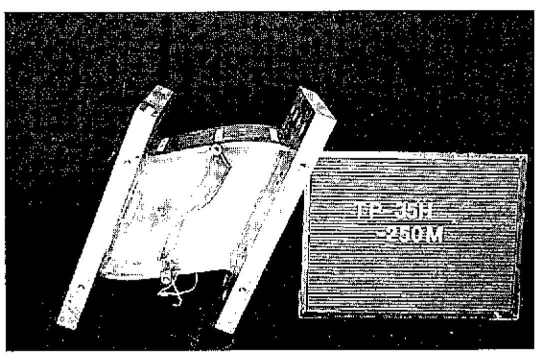


Photo 4 Specimen LYP100-C-2 after test

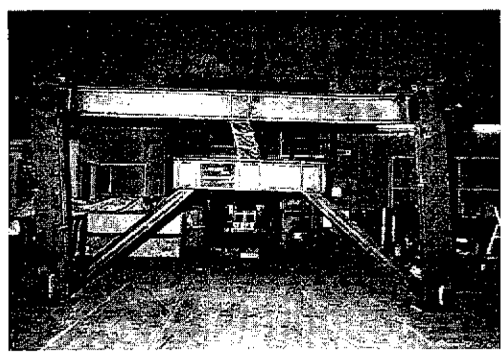


Photo 5 Failure of specimen B

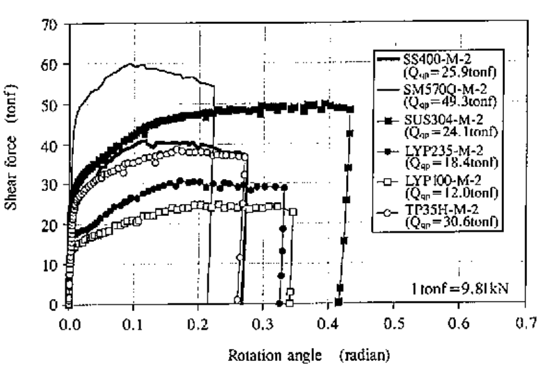


Fig. 14 Relationship between shear force and rotation angle (aspect ratio of 2)

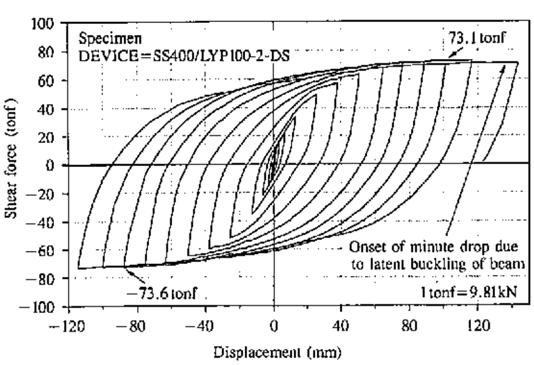


Fig. 15 Relationship between shear force and story displacement

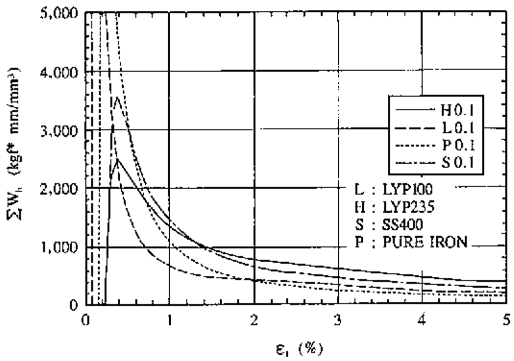


Fig. 16 Relationship between cumulative hysteresis energy (ΣW_h) and total strain amplitude (ε_t)

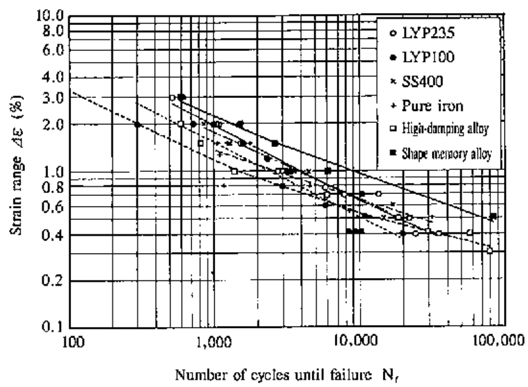


Fig. 17 Comparison of low-cycle fatigue properties of iron-based alloys

of steels calculated from low-cycle fatigue test results are given in **Fig. 16**. The cumulative amount of energy absorbed until failure is shown in relation to the strain amplitude. The relative advantage of these steels is reversed, depending on the strain amplitude. The fatigue properties of iron-based alloys are comparatively shown in **Fig. 17**. The iron-based alloys differ in the number of cycles until failure. These phenomena suggest one possibility of applying the energy absorption performance of steels.

6. Ceramic Friction Dampers

Together with Tokyo Kenchiku Structural Engineers and Yuu Engineering, Nippon Steel has developed a new friction damper for vibration control. When friction dampers are used to control the vibration of buildings, they must provide friction force stability at a low velocity, and high durability.

To achieve this the Ceramics & Metals Lab. at the Advanced Technology Research Laboratories worked on the development of appropriate friction materials and created a ceramic friction material (SCO-3-4) that has a stable friction coefficient and features excellent wear resistance and durability. Ferritic stainless steel (YUS410W with #150 surface roughness) was selected as a wear-resistant sliding material. When the ceramic friction material SCO-3-4 was reciprocally friction tested at the contact pressure of 30 kgf/cm², as in the pattern (over 11,850 cycles) shown in **Fig. 18**(a), and for three runs as shown in **Fig. 18**(b), its friction coefficient was found to be extremely stable with a minimum of dependence on sliding speed as shown in **Fig. 19**. A load controlling washer (BT washer) containing a disc spring with a load calibrating ring was adopted as the clamping device to control the load, and the variation in the clamping force is relaxed during sliding.

At present, full-size ceramic damper specimens are undergoing detailed tests to establish performance parameters such as contact stress, amplitude and frequency, and to understand the effects of

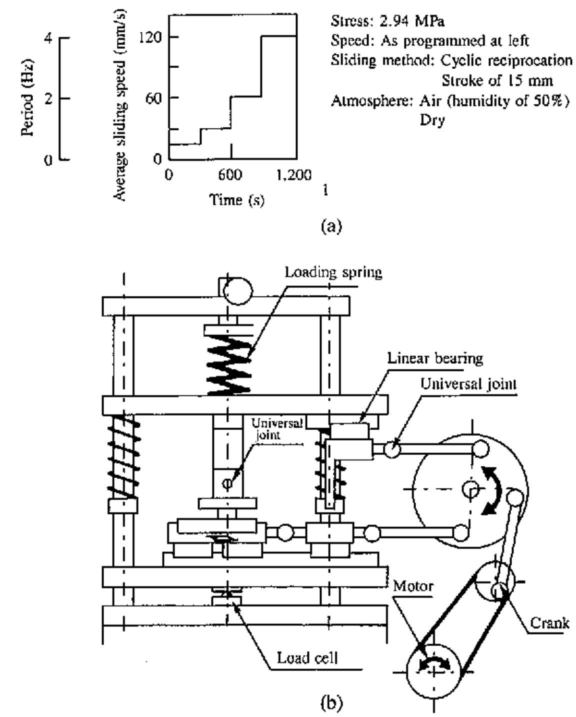


Fig. 18 Horizontal load versus horizontal displacement

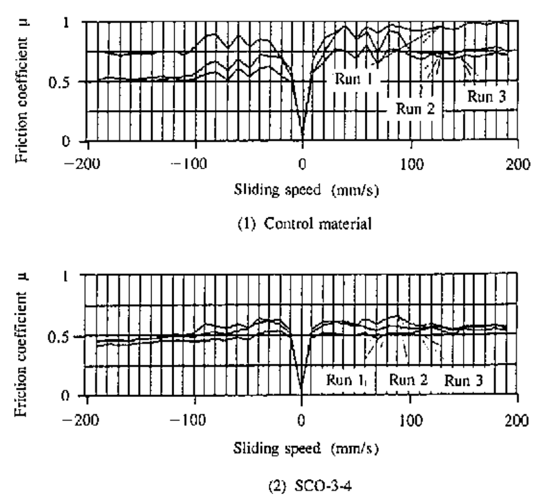


Fig. 19 Relationship between friction coefficient and sliding speed

ambient temperature and humidity. The ceramic pieces are joined to steel sheets as shown in **Photos 6** and **7**.

The newly developed ceramic material is difficult to gall has an extremely stable friction coefficient, and is barely affected by speed and displacement (see **Fig. 20**). Its energy absorption can be easily and accurately measured. Its high durability and cyclic performance are believed to make it an ideal vibration control element against small and medium earthquakes and typhoons. The test results of the ceramic friction damper will be reported on another occasion.

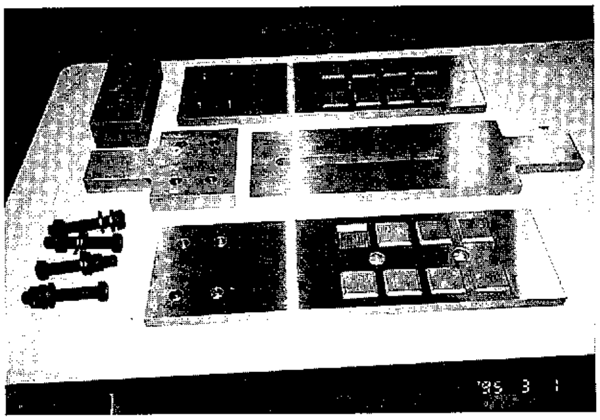


Photo 6 Friction damper specimen

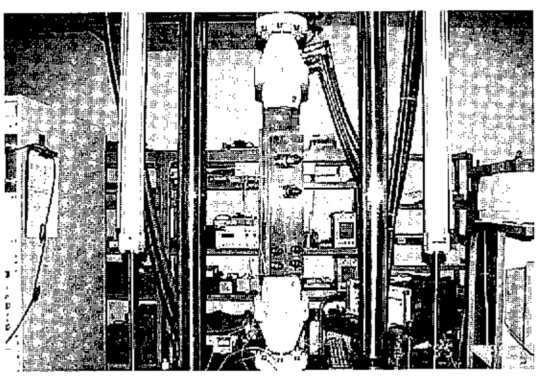


Photo 7 Specimen being tested

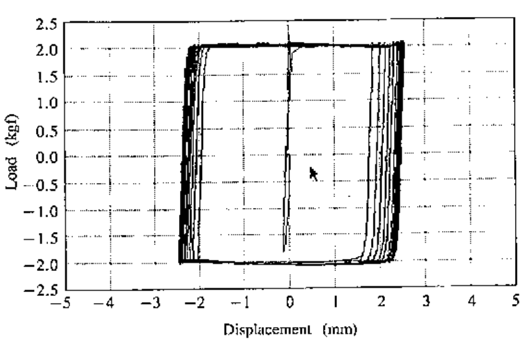


Fig. 20 Load-displacement curves

7. Tuned Liquid Dampers

The tuned liquid damper (TLD) is a liquid-filled container that is placed on the top of a building.It absorbs the vibration energy of the building by tuning the natural frequency of the liquid with that of the building, and prevents the horizontal shaking of the building (see **Fig. 21**). The TLD effectively responds to even small vibrations. When the TLD shakes excessively, it needs no special stoppers. Its greatest advantages are low installation cost and easy maintenance.

For the TLD to be effective in controlling the vibration of a building, its effective mass must be about 1% of the primary generalized mass of that building. The TLD is particularly effective in controlling the vibration of relatively lightweight and predominantly bending structures such as sightseeing towers. Under the guidance of Professor Tamura of the Tokyo Institute of Polytechnics, Nippon Steel jointly developed a specially shaped TLD with Nippon Steel Chemical Co., Ltd. Two plastic doughnut-shaped containers were concentrically connected and blow molded into a one-piece TLD (see **Photo 8**). This special shape

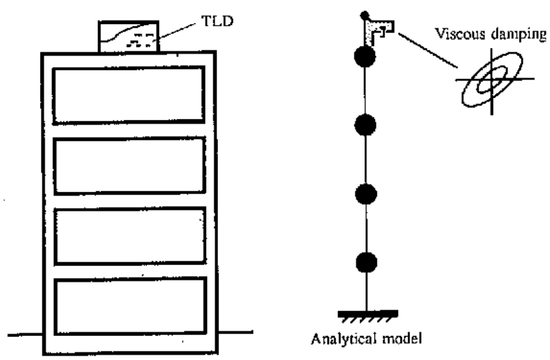


Fig. 21 Characteristics of tuned liquid damper (TLD)

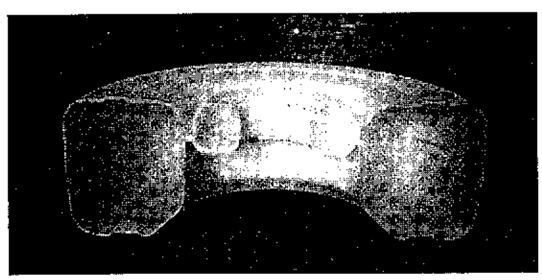


Photo 8 Cross section of TLD

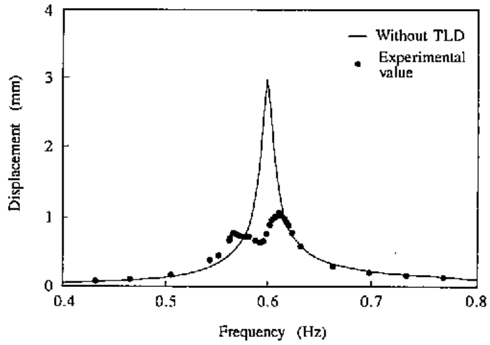


Fig. 22 Relationship between frequency and displacement

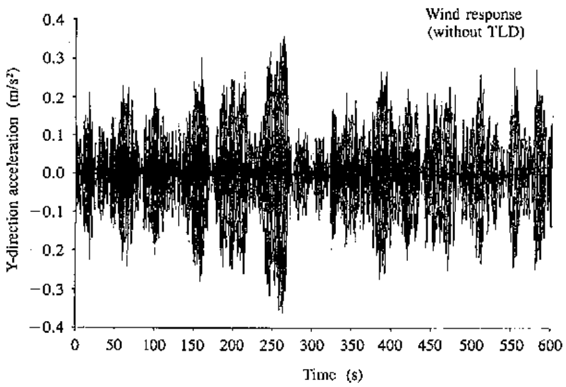


Fig. 23 Time history acceleration without TLD

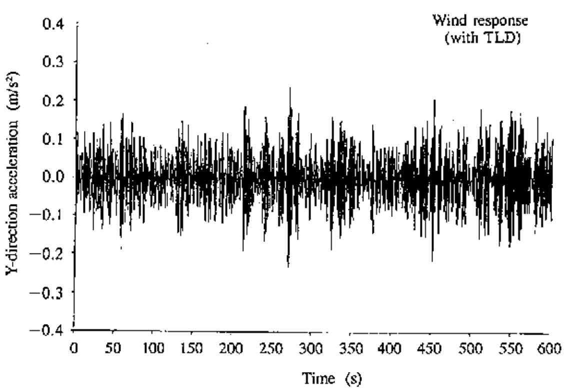


Fig. 24 Time history acceleration with TLD

enhances the damping effect of the TLD and reduces the vibration of a building effectively (see **Fig. 22**). To perform frequency tuning, the frequency of the building is measured, and the water depth in the TLD is adjusted to meet the measured frequency. Some floating objects can also be added to the TLD to increase damping capacity. When installed outdoors, the TLD is coated with weathering paint to prevent ultraviolet degradation.

The wind response analysis of a 115-m tall tower now in the planning stage shows that a TLD would reduce the root-mean-square (RMS) value (standard deviation acceleration) of the tower top by about 60% against the wind velocity of 25 m/s for a return period of 1 year, and would be effective in damping the vibration of the tower (see **Figs. 23** and **24**).

8. Conclusions

Devices related to earthquake resistance, vibration control, and isolation have been discussed with emphasis placed on steels and advanced materials. In the development of an energy absorption system for a building, the optimum combination of design, manufacture and fabrication is as important as material development. To meet the ever increasing needs in this field, we will continue to develop new materials and devices in cooperation with those in and outside of Nippon Steel.

Reference

1) Shinnittetsu Giho. (351), 51 (1994)