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Seismic Control Devices Using Low-Yield-Point Steel

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Abstract:

With the purpose of developing seismic control structures that utilize the hysteresis energy absorption of steel products, this paper explains the development of new steel products for seismic control devices (dampers) and shows the performances and typical applications where such devices have been put to actual use. The authors investigated the properties required of steels for seismic control devices, developed two kinds of steel, LYP 100 (YP = 100 N/mm² class) and LYP 235 (YP = 235 N/mm² class), which have lower and narrower-range yield points (YP) and better elongation than conventional steels, and discuss their material properties. The authors also show the test results of the material properties of the new steels that relate to seismic control devices such as hysteresis characteristics, strain rate dependency, low-cycle fatigue characteristics and weldability. They then outline the development of unbonded braces and seismic control walls and panels as examples of seismic control devices using the new steels, as well as the structural characteristics of each device. Finally, they introduce typical examples of actual designs which use these devices, demonstrating the seismic control effects of the devices using LYP steels.

1. Introduction

Conventional structural design of buildings in Japan achieves seismic performance by absorbing seismic energy, with the plastic deformation of the columns or beams of buildings. The damage in the Kobe Earthquake made it clear that conventional structural design (cf. **Fig. 1**(a)) which deforms and plasticizes such major structural members made it very difficult for repairs after the disaster. Also controlling seismic performance which corresponds to the importance level of buildings is difficult with the current design technique. As a solution to this problem, seismic control structures (cf. Fig. 1(b)) with seismic control devices (dampers) into buildings have been getting attention. The seismic control structures are designed to achieve seismic performance by making the devices absorb the seismic energy. This makes it possible to specify part materials for energy absorption, which has been ambiguous with conventional techniques, and to control seismic damage by identifying the performance. Also, specifying damaged positions facilitates repairs.

Seismic control structures are thus expected to be a key to future seismic design. Nippon Steel Corporation has been the first to conduct studies on seismic control structures that absorbing the hysteresis energy of steel products, and has developed a new steel product for this application. As a result of a 10-year-study, Nippon Steel has developed a new steel product for seismic control devices. Furthermore, Nippon Steel has evolved the seismic control devices using the new steel products into joint studies with major users. As of 1998, Nippon Steel has achieved over 40 applications in skyscrapers.

This report describes the results of the low-yield-point (LYP) steel developed for seismic control devices and seismic control technical development using these products.

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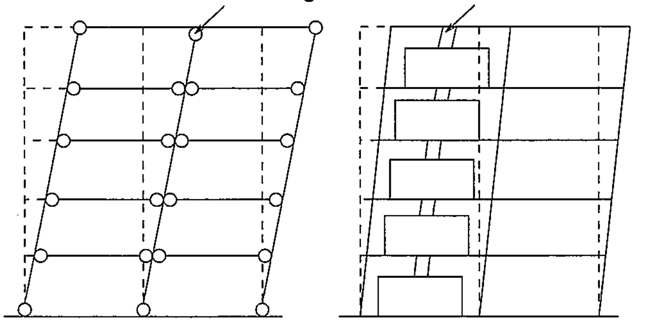


Fig. 1 Comparison of seismic design

Table 1 Chemical composition of LYP steel (Nippon Steel Corp. standard)

(mass%)

Steel type		C	Si	Mn	P	S
BT-LYP100	Nippon Steel standard	≤0.02	≤0.02	≤0.20	≤0.030	≤0.015
	Actual example	0.001	0.01	0.08	0.008	0.005
BT-LYP235	Nippon Steel standard	≤0.10	≤0.35	≤1.40	≤0.030	≤0.015
	Actual example	0.017	0.008	0.38	0.017	0.006

Table 2 Mechanical properties of LYP steel (Nippon Steel Corp. standard)

Steel type	Yield point (N/mm²)	0.2%offset proof stress (N/mm²)	Tensile strength (N/mm²)	Elongation at fracture (%)
BT-LYP100	—	80-120	200-300	≥50%
BT-LYP235	215-245	—	300-400	≥40%

JIS Z 2201 No. 5 test piece should be used.

2. Development of BT-LYP 100 and BT-LYP 235

2.1 Required performance of steel products for seismic control devices

The performance required of steel products for seismic control devices which will absorb hysteresis energy is, from the aspect of structural design, as follows: First of all, because the seismic control devices are passive to seismic input, preceding other structural part materials such as columns or beams and plasticizing at the designed stress level are feasible even with normal steel hysteretic dampers. But the use of a steel product which possesses a clearly lower yield strength and tensile strength than other structural part materials can easily achieve the above.

For this reason, it is necessary that yield strength should be low and scattering of yield point (YP) should be limited as narrowly as possible (narrow yield point). For a large earthquake, the device is going to undergo great repeated deformations in the plastic region, thus needs excellent elongation and low cycle fatigue characteristics. Workability and weldability necessary for construction are also required. Steel products for seismic control devices are intended to be used in the plastic region, which gives rise to the question of whether it is proper to follow the standardization for conventional steel products. Even at this time in 1998, accurate required performance figures have not been authorized. Therefore, based on manufacturing technical data on works, new materials which possess the above required performances, two specifications for steel products, BT-LYP 100 and BT-LYP 235 in **Tables 1 and 2** (hereinafter BT- will be omitted, described as LYP 100 and LYP 235 and both abbreviated as LYP steel) have been established as development objectives for Nippon Steel's internal use[1)].

LYP steel has adequate low yield strength and tensile strength, while a steel product (e.g. SN490) whose tensile strength is in the 490 N/mm² class, and normally used for building structures. The reason for developing two kinds of steel products with different strengths is that freedom of selecting design strength in seismic control devices is necessary. It is possible that the chemical composition and mechanical characteristics in **Figs. 1 and 2** will be revised, including the material test methods for regulation items or figures while these materials are becoming more popular. However, as of 1998, users are evaluating the specifications of the steel products as almost pertinent by design. The materials since developed by other manufacturers have been nearly similar, making the Nippon Steel standards virtually de-facto specifications.

2.2 Material properties of developed steel products

1) Characteristic of base materials for LYP steel

The material quality of LYP steel has been improved successively in response to the development and application of various types of seismic control devices that use LYP steel. The characteristic of the chemical composition is that both of the LYP steels have a composition system (cf. Table 1) that is nearly pure iron with very negligible carbon and alloy elements. Fig. 2 shows the yield strength and the frequency distribution of percentage elongation at fracture of the LYP steel manufactured recently.

Although in the manufacturing data the plate thickness of the targeted materials have a wide range of thickness, 6 to 50 mm, the yield points stay within a very narrow targeted range, which is evidence of the established stable manufacturing technique.

Fig. 3 shows LYP stress–strain curves compared to other steel products. Because LYP 235 has yield points, but LYP 100 is a roundhouse with unclear yield points, the yield strength is taken at the time of 0.2% offset strain. Compared with other steel products, both have a bigger stress increase as a result of work-hardening after yield strength, this characteristic is apparent in device hysteresis characteristic. **Fig. 4** shows the transition curves of the absorbed energy in the Charpy impact test. Both LYP 100 and 235 possess very good material impact characteristics. Yet such seismic control devices as have fast strain in thick materials and have a fatigue notch like weld joint must sometimes consider brittle failure and the ductility of base materials will be required.

The characteristics of the base materials that affect the performance of seismic control devices using LYP steel include hysteresis characteristic, strain-rate effect and the characteristic of low-cycle fatigue. The relationship between strain and stress in the fixed amplitude low-cycle fatigue test, with the amplitude parameter, is shown in **Fig. 5**[2)], and compared with the monotonic loading test results. In the same way as normal steel products, repetition after a virgin loop causes hardening and the regular loop is made as in **Fig. 6**[3)] after 4 to 5 cycles. The values in Fig. 5 plot the biggest stress and strain on the 20th cycle. The characteristic of hardening has a tendency similar to actual devices, but it is a little higher than the conventional steel products. In design, the structural performance test is conducted corresponding to the device type, e.g. axial or shear to set up hysteresis

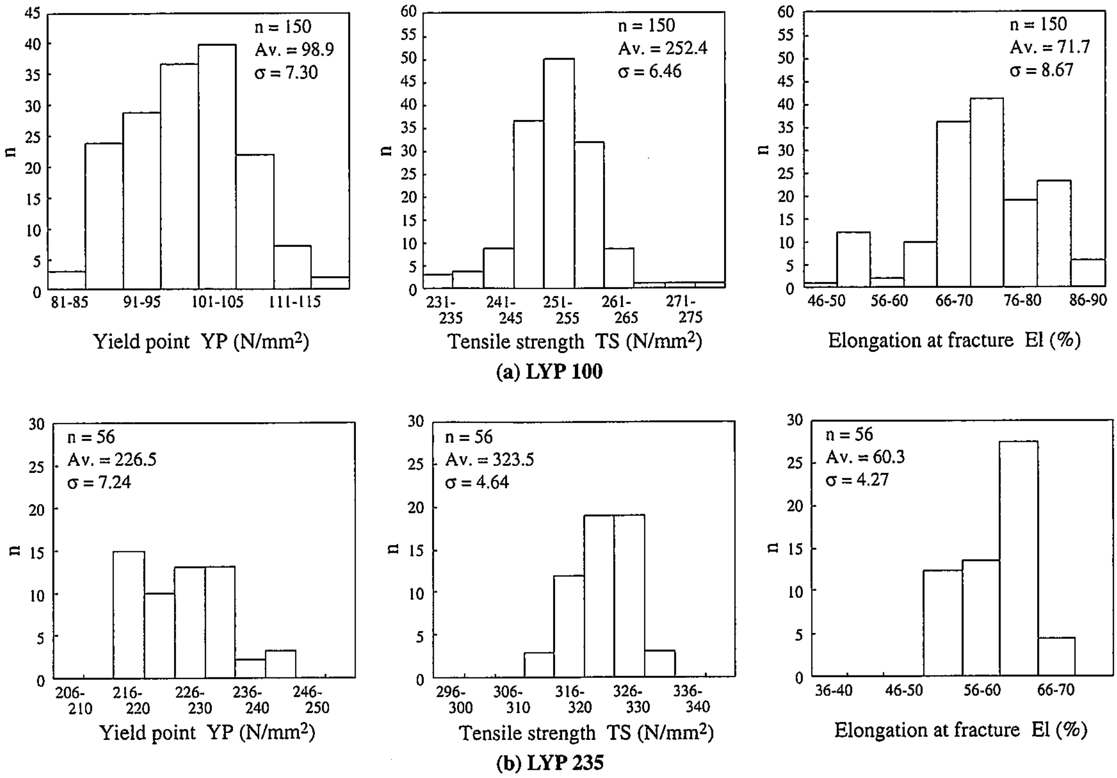


Fig. 2 Production results of LYP steel

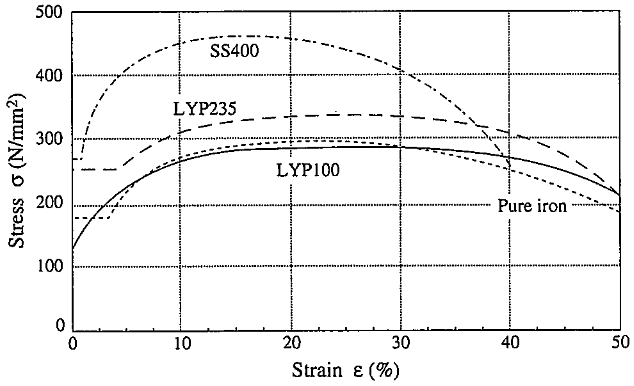


Fig. 3 Stress-strain curve of LYP steel

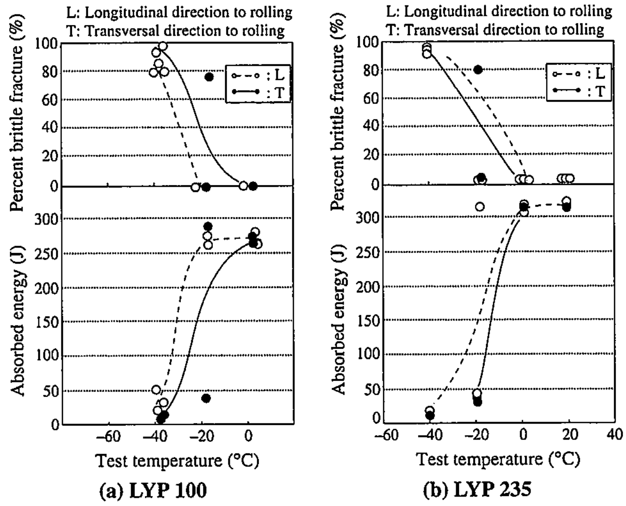


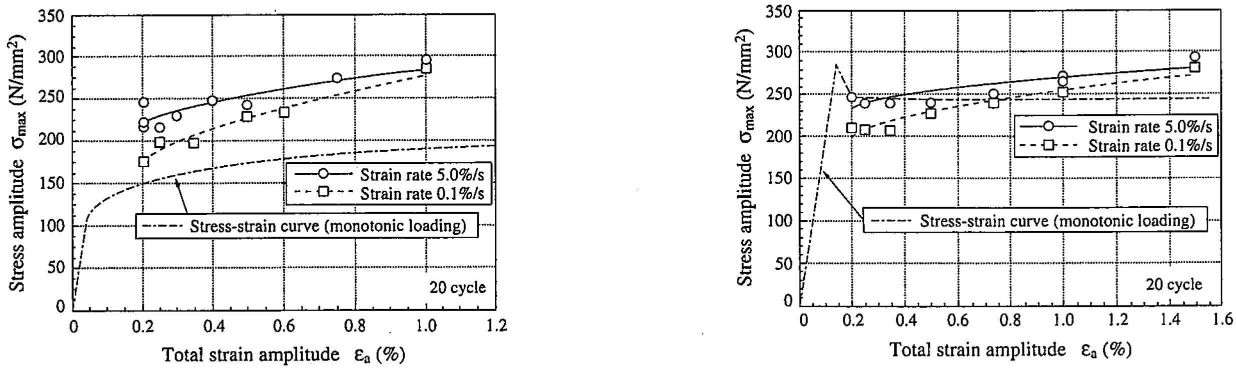
Fig. 4 Transition curve of absorbed energy in Charpy impact test of LYP steel (plate thickness: 25 mm)

performance data for each device.

Fig. 7[4] is the research results on the strain-rate effect of LYP steel. The increase of yield strength and tensile strength in response to a is comparatively bigger than such conventional steels as SM490, whose effect must be considered according to the conceivable strain-rate of devices[5]. But it has been confirmed that percentage elongation after failure or uniform elongation have a small effect from strain-rate. **Fig. 8**[2] shows the low-cycle fatigue test results for base materials and the regression curve of repeated numbers from strain-amplitude to failure. Both LYP 100 and 235 have low-cycle fatigue characteristics similar to SS400. The actual design conducts the fatigue test for each device type to set up the design life.

2) Weldability and weld joint performance of LYP steel

LYP 100 and 235 have very negligible carbon or additive elements in their chemical composition and no particular weldability problem. But in the case of the actual device fabrication, the same steel products as LYP 100 and 235 or the different ones like SN490B are welded, so the weld joint test was conducted to confirm the performance. **Table 3** shows the test results for butt joints of LYP 100 and 235. In the weld joint tensile test, each has base material failure and joint intensity is also noted. Good weldability was confirmed as well, in the weldability test results of a hardness test and y-groove cracking test. **Fig. 9** shows the bonds of LYP 100 and 235, as well as



(a) LYP 100 (b) LYP 235

Fig. 5 Relationship between stress amplitude and total strain amplitude

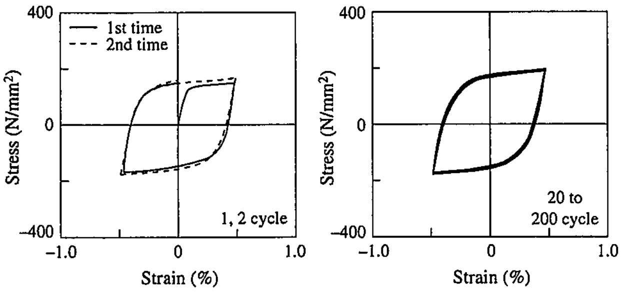


Fig. 6 Hysteresis curve (Example of LYP 100)

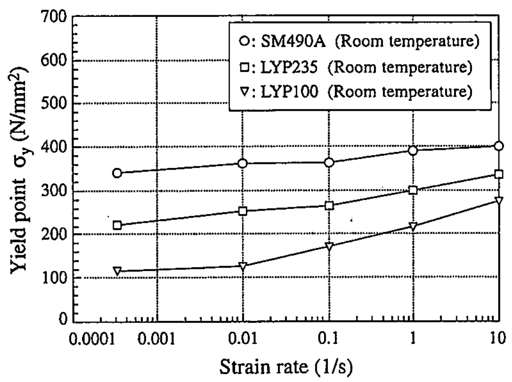


Fig. 7 Strain-rate effect of LYP steel

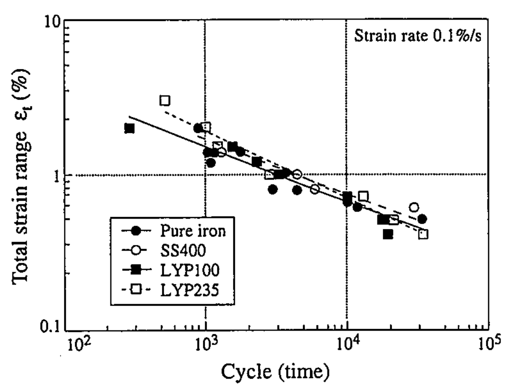


Fig. 8 Low cycle fatigue test of LYP steel

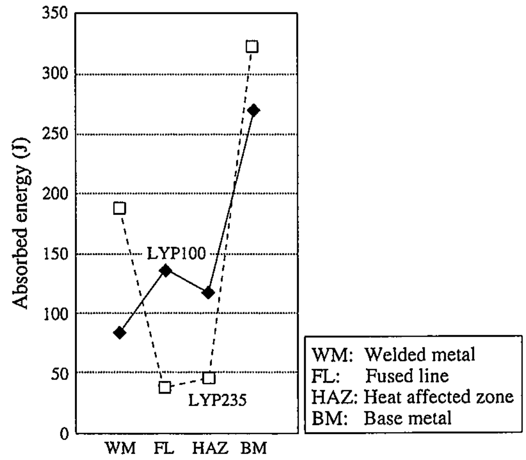


Fig. 9 Absorbed energy in Charpy impact test of LYP steel welded area

the absorbed energy in the Charpy impact test in the heat-affected zone. Welding lowers the values of the base material area. This is because the base material system is damaged by the welding heat and care must be taken for a butt joint for a device of an axial yield strength type. The high-speed tensile test results[6] for a brace material using low toughness LYP 100 show no occurrences of brittle failures up to minus 40 centigrade, however the performance of the welded area should be a future agenda.

3) Processing LYP steel

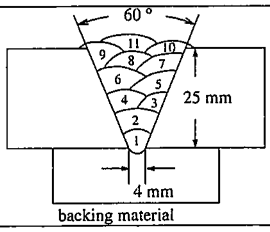
LYP is often designed with relatively thin thickness, around 6 to 12 mm and its small yield strength is apt to cause deformation during shipping and processing. So the processing plant must be more careful with LYP handling than with ordinary structural steel products. It is also necessary to minimize the strain correction by heating and cooling to prevent material changes caused by the heat. With such care, processing and assembling LYP steel can be done in the same way as conventional steels.

3. Developing Seismic Control Devices

3.1 Development of seismic control devices using LYP steel

Fig. 10 shows the types of seismic control devices developed using LYP steel up to now, by Nippon Steel, various construction companies and design offices[7]. Types of part materials can be classified into steel products that have axis yield ((a) in the figure) and products that have shear yield ((b) to (e) in the figure). A typical

Table 3 Welded joint test results

Type of steel Plate thickness	Welded material	Welding condition Current-voltage-speed	Groove shape and laminating method	Tensile test result : Fracture strength	Fracture position
LYP100 t = 25mm	YM-26 1.2mmϕ	280A-32V-25cm/min Heat input 21kJ/cm		283N/mm²	Base metal
LYP235 t = 25mm		300A-32V-28cm/min Heat input 20.6kJ/cm		353N/mm²	Base metal

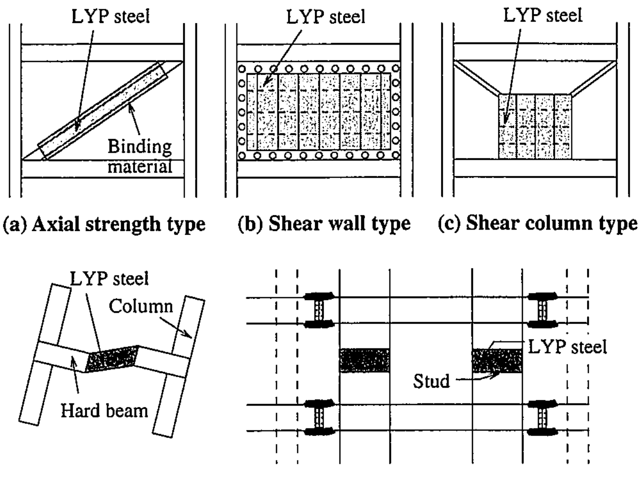


Fig. 10 Types of seismic control devices using LYP steel

device of the axis strength type is the unbonded brace which is described later. The shear type device has panels with shear board reinforced from outside with ribs or surrounding plates.

The part materials of each type are assembled in a processing plant and on site they are attached to surrounding frames with gusset plates and friction bolts. The devices of the shear type, which are often used, as is shown in (c) to (e) in the figure, have shear panels intensively set up between part materials to make deformation concentrated and facilitate replacement.

The hysteresis characteristic differs according to the yield types or concentration level of story deformations. If the yield axis strain of LYP 100 is set at 0.05% when making models of bilinear load-deformation relationship, the story drift angle (shear composition) of a frame is about 1/1000 at the initial yield of the devices of the axial strength type which are arranged at an angle of 45° spanning every story. The plastic deformation rate is about 10, in relation to 1/100, the deformation limit in a level 2 earthquake. On the other hand, the yield deformation angle of a shear wall which spans every story in the same manner, is around 1/1400 and the plastic deformation rate in relation to the story deformation 1/100 is about 14. So, generally speaking, while shear type devices begin yield at an earlier level than the axial strength type, they have a bigger cumulative plastic rate per loop and inferior deformation repetition capability. This tendency is more apparent in the case of intensive shear panels, some panels have a plastic deformation rate of over 100 in relation to the frame deformation angle at 1/100.

The devices with an extremely big plastic rate in relation to the biggest deformation angle estimated in this way should be noted for the local buckling impact of panels, the strain concentration in welded areas and greatly lowered repetition capability.

In contrast to LYP 235 with its small hardness, LYP 100 has a large work-hardening and strain rate effect, which necessitates designing for not only the bottom limit of the yield point but also the upper limit (about 200 N/mm²).

The two types of part materials developed at Nippon Steel are detailed below:

3.2 Developing unbonded braces using LYP steel

Unbonded braces are axial hysteretic dampers which are made of flat plates or cross core materials, bound with steel tube concrete through unbonded materials to avoid buckling (cf. **Fig. 11**). As seismic resistant members and seismic control devices with the precise equivalent hysteresis characteristic in both tension and compression, unbonded braces were developed by Nippon Steel in 1986 and have been applied to over sixty buildings since then[8]. SS400 or SM490 are often used for core materials and the general authorization by Japanese Ministry of Construction for structural members is acquired in this capacity. Recently, use of LYP 100 and LYP 235 for core materials has been increasing in order to decrease the seismic response by plasticizing at a tremor with less than level 1 and to assure the yield at the intended earthquake level in design.

Fig. 12 shows a practical-scale experiment of the unbonded braces using LYP 100 as the core materials and the load-deformation relationship at the time of static repeated loading[7]. The effect from the work-hardening is a little more apparent than with normal steel but the extremely stable spindle-shaped loop can be obtained. Fatigue and other experiments on part materials have confirmed that the repeated deformation capability in relation to strain amplitude ± (equivalent to story deformation angle 1/100) totals over 200 times or so (cumulative plastic rate is about 7200)[9].

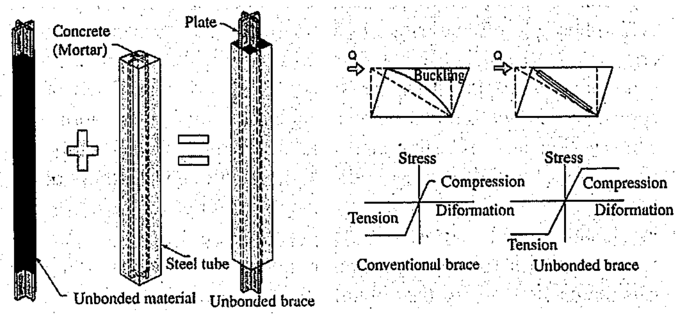


Fig. 11 Unbonded braces

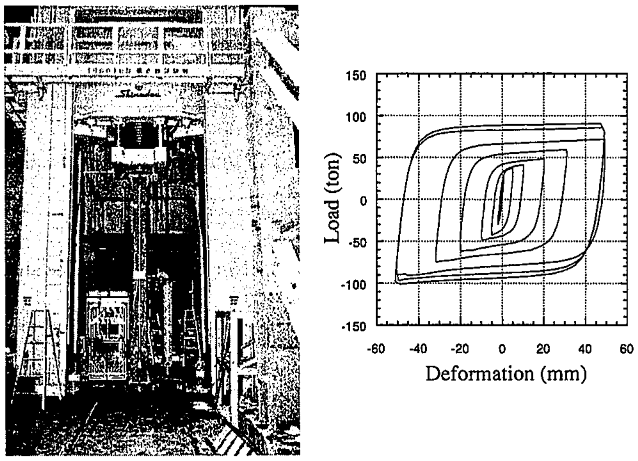


Fig. 12 Experiment of practical-scale unbonded braces using LYP 100

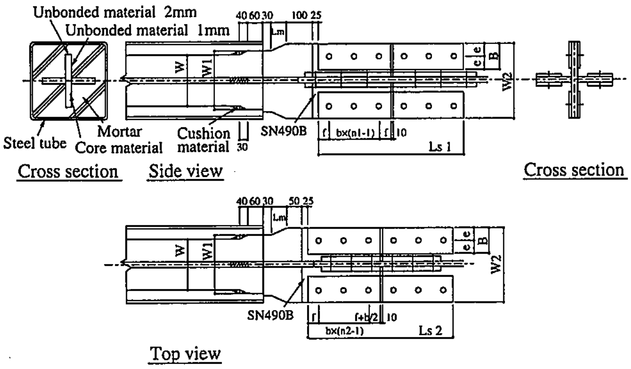


Fig. 13 Detailed example of unbonded brace edges using LYP 100

Fig. 13 shows the detailed example of unbonded brace edges using LYP 100 as the core materials (cross type). To prevent bolt slips as a result of developing initial strain, normal steel (SN490B) is used for the edges, which are connected to the core materials by butt joint welding. And the core materials inside the bound materials are made to have preceding yield and in order to keep the stress in the welded areas under a certain level after the work-hardening of the core materials, two steps of haunch are set in core material edges and the welded cross section 1.5 times as large as the core materials is secured.

3.3 Developing response control walls and stud device using LYP steel

As to the shear type panels, in addition to making the wall type in Fig. 10(b) a standard item for general use, the stud type in Fig. 10(c) is also being jointly developed with design offices and construction companies. **Fig. 14** shows the detailed example of attaching the wall type using LYP 100, the three-story shear load experiment of response control walls and the obtained load-deformation relationship. The shear panels have rib plates attached on the front vertically and on the back horizontally. The ratio of the width and thickness of the bound panels should be 80 and the range is set up so as not to cause local buckling, which precedes the shear yield of the panels. The ribs are designed not to cause buckling of the overall walls, including the ribs themselves. As for the obtained restoration strength characteristic, in relation to the biggest deformation angle 1/75, the stable loop, a cumulative plastic deformation rate up to around 250 was confirmed.

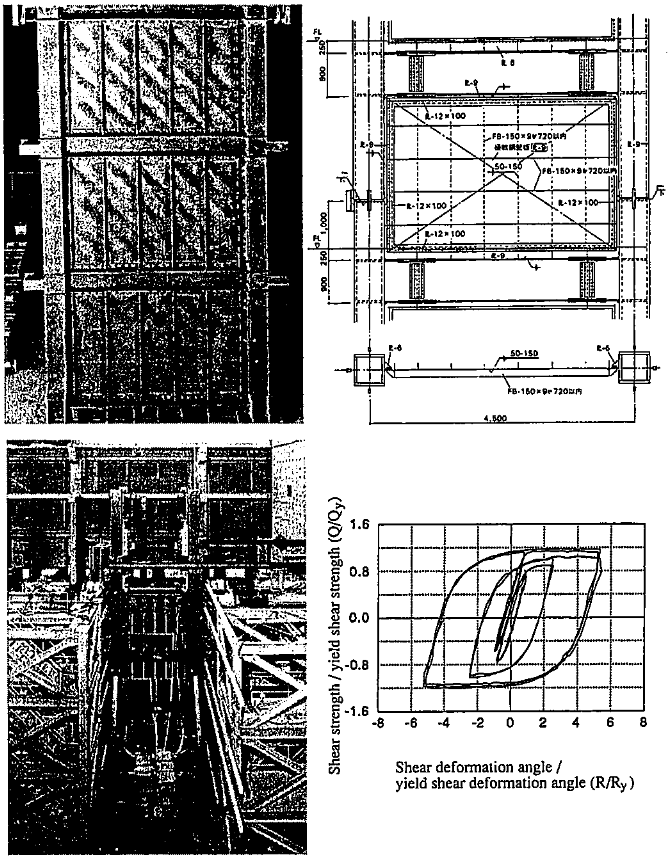


Fig. 14 Load test of shear wall using LYP 100

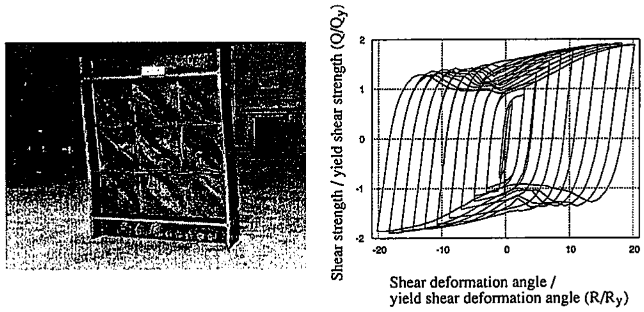


Fig. 15 Load test of shear column using LYP 100

Fig. 15 shows the results of a shear repetitive strength addition experiment on the stud type devices, also using LYP 100. The ratio of the width and thickness of the panels is 66 and the repetitive gradually increasing load with the biggest plastic rate up to 20. Fig. 15 shows a stable spindle-shaped restoration strength characteristic up to the cumulative plastic rate of 170, but after that, as the local buckling of the panels progresses, the loop changes to a double enveloping worm and at the cumulative plastic rate of 800, the failure in local buckling occurs. This is equal to about 30 times the repetition capability of the plastic rate +7 (equivalent to story deformation 1/100) and is about one sixth of the previously mentioned unbonded braces.

4. Application to Actual Buildings

4.1 Passage Garden North 1st Section[10]

Building design: Plantech

Structural design: Alpha Structural Design

Collaboration: Nippon Steel Corporation

This is an office building with 14 stories above ground and 2 floors underground, 63 m in height and about 10,000 m² in total floor area, in front of Shibuya Station. The entire building is supported by the outside slanted lattice frames. This outside frame is designed to be expressed as outer design (cf. **Fig. 16**(a)).

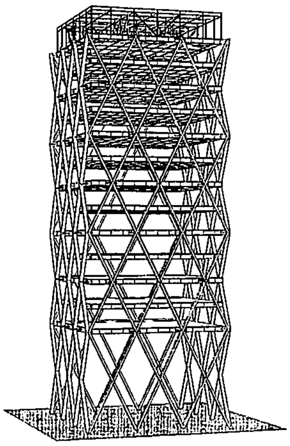
The outside frame must not only support the building's own weight, but must also resist the lateral strength of an earthquake, and all part materials must be axial strength part material. The buckling of the lattice material in an earthquake loses the independence of the building and leads to the overall collapse, which must be avoided. On the other hand, since it is not economical to have all the part materials be elastically designed against level 2 stress, the damage tolerant design with unbonded braces which use LYP 100 was applied to realize an economical frame.

Fig. 16(c) shows the structural planning outline. Into part of the lattice unbonded braces are inserted as seismic control devices and the preceding plasticizing of this part ensures the absorption of earthquake energy and avoids the buckling of the other part materials that support the building. As a result, the effects of hysteresis damping and longer period of the device decreased the base shear of level 1 to about half of that of an elastic design without a seismic control device. The LYP 100 used for the unbonded brace core materials are flat plates, 500 mm wide, 40 mm thick, and about 9 m long. These part materials begin plasticizing at an earthquake less than level 1 and reach the biggest plastic rate of 3.4 at a level 2 tremor. On the other hand, other part materials supporting vertical load materials stay at an axial strength of less than around half of buckling load, even with a level 2 tremor. And it is estimated that the biggest strain rate occurring in seismic control part materials is about 0.7%/s at level 2 earthquake.

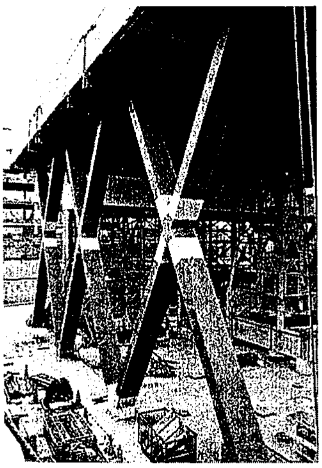
This building has cumulative axial transition measuring equipment attached, separately developed by Nippon Steel, to control the cumulative plastic rate of the seismic control device against wind load or minor earthquakes[11].

4.2 Saitama Wide- area Joint Agency Buildings[11]

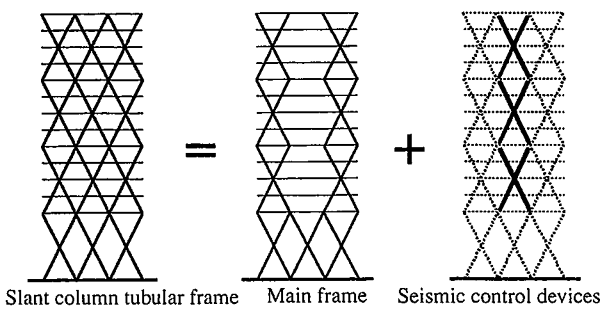
Building / Structural Design: Kanto Region Construction Agency,



(a) Frame outline

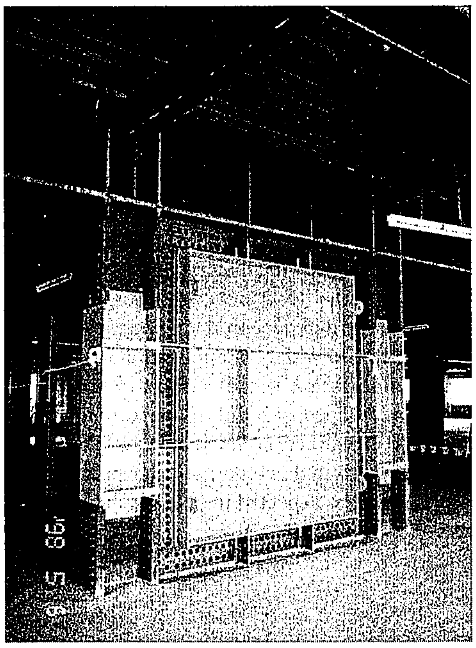


(b) Actual site



(c) Damage level control design

Fig. 16 Application cases of LYP steel unbonded braces



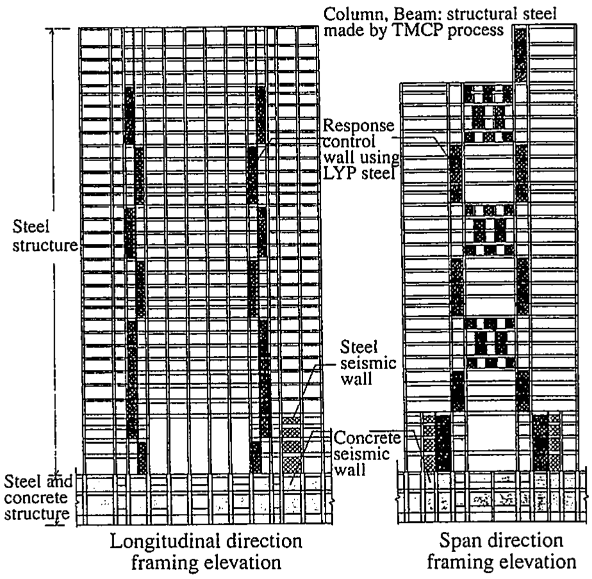


Fig. 17 Application cases of LYP steel response control wall (Saitama Wide-area Joint Agency Buildings)

Nikken·Tohata·RTKL joint venture

There are two agency buildings: one with 31 stories above ground and 2 floors underground, and about 120,000 m^2 in total floor space, and the other with 26 stories above ground and 3 floors underground, and about 130,000 m^2 in total floor space. By putting the response control walls which use LYP 100 around the stairwells, both buildings are constructed to decrease story deformations in a big earthquake and curtail remaining deformations after the quake (cf. **Fig. 17**).

The LYP 100 used for the Response Control Walls is 6 to 25 mm thick and about 4.5 m × 3 m in area, reinforced by vertical and horizontal ribs, and connected to the surrounding frames by friction bolts. In the same way as LYP-100 unbonded braces, the gusset plates in the friction joint area use normal steel. These devices are arranged around the stairwells which can easily concentrate stress within the frame. And arranging the devices in a grid against the front side minimizes the decrease of their effect by bending deformations. As a result, the devices begin plasticizing in an earthquake with less than level 1 and the highest velocity is about 15 cm/s. But they have elastic design against wind load. The result of the response analysis confirmed the effect of decreasing displacement about 30% at maximum, compared with structure without the response control walls.

4. Conclusion

This paper has described the material characteristic of LYP steel, the actual situation of the R&D and practical application of seismic control devices that use this steel product. Such seismic control structures are likely to spread widely in application from high-rise buildings to general buildings, as a seismic design technique that responds to the requirement to specify building performance following the amendment of the Construction Standard Law. The seismic control devices using LYP steel in this report are cheaper and more dependable than others, and are expected to become major devices.

The future research agenda involves clarifying the required performance of steel products, unifying the standards of steel products, grasping the dynamic characteristics and generalizing the design methods.

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