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Development and Application of "Super-Elastic Brace" for Steel Buildings

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Abstract

In steel framed buildings, braces are widely used as a main earthquake- resistant element. Brace structures are economically superior to pure moment resisting frame structures. In conventional brace structures, however, stiffness is much greater in braces than in the frame and therefore most of the seismic forces concentrate in the brace. Well-balanced arrangement of braces in the building is therefore required. Conventional braces yield due to small deformation at a story drift angle of approximately 1/500 rad. No braces can therefore be arranged in small numbers because of the restrictions of the first design that allow no yielding of members. In cases where only a few braces can be arranged or no well-balanced arrangement of braces is possible because the appearance or functions of the building are given priority, therefore, pure moment resisting frame structures are adopted abandoning the use of brace structures. To solve the problem, expanding the range of elasticity to prevent seismic forces from concentrating in the brace is effective.

The authors developed a "super-elastic brace" that would not yield at a story drift angle of less than 1/200 rad. The super-elastic braces are composed of three steel elements of different diameters (core, middle tube and outer tube from the inside) (Fig. 1). The three steel elements are connected traversability to each other to increase the actual length (2.5L) of the member to 2.5 times the apparent length (L). Elastic limit displacement is increase in proportion to the member length. Therefore, Elastic limit displacement of the super-elastic braces is 2.5 times compared to the conventional braces. In this way, braces that would not yield at a story drift angle of less than 1/200 rad are realized. In addition, from a structural viewpoint, axial forces of adjacent steel elements offset each other in compression and in tension, and as a result, buckling is controlled. Super elastic braces operate stably even at large deformations of 1/50 rad. Using super-elastic braces enables the application of fewer braces and the eccentric arrangement of braces. A rational brace structure is thus realized.

This paper outlines the super-elastic brace. Also, described are a structural test conducted to verify the performance of super-elastic braces applied to an actual building. In addition, this paper describes an example of application of super-elastic braces in an eight-storied newly constructed steel framed office building.

Keywords: Steel building, Brace structure, Super-elastic, Yield displacement, Buckling restraint

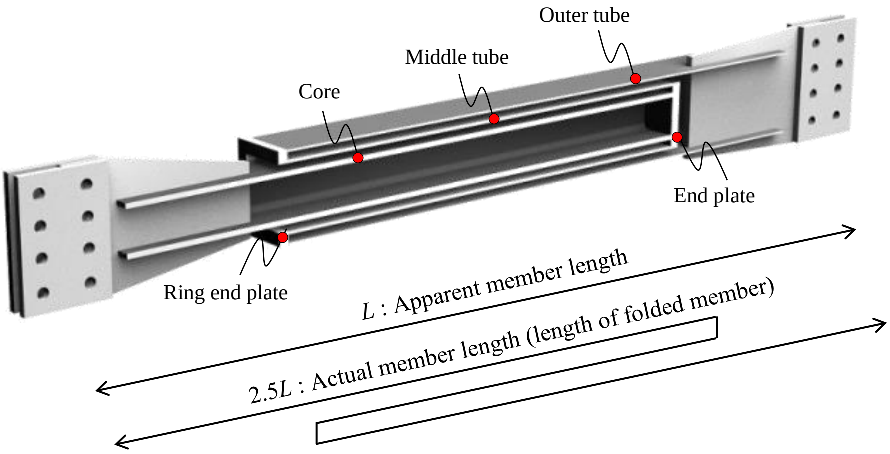


Fig. 1 – Crass-sectional perspective of super-elastic brace

1. Introduction

In Japanese steel frame buildings, brace structures that use braces as a seismic element in a moment resisting frame are generally used. Brace structures are economically superior to pure moment resisting frame structures. In conventional brace structures, however, stiffness is much greater in braces than in the frame and therefore most of the seismic forces concentrate in the brace. Well-balanced arrangement of braces in the building is therefore required. Conventional braces yield due to small deformation at a story drift angle of approximately 1/500 rad. No braces can therefore be arranged in small numbers because of the restrictions of the first design that allow no yielding of members [1] [2]. In cases where only a few braces can be arranged or no well-balanced arrangement of braces is possible because the appearance or functions of the building are given priority, therefore, pure moment resisting frame structures are adopted abandoning the use of brace structures. To solve the problem, expanding the range of elasticity to prevent seismic forces from concentrating in the brace is effective [2].

The authors developed a “super-elastic brace” that would not yield at a story drift angle of less than 1/200 rad. Using super-elastic braces enables the application of fewer braces and the eccentric arrangement of braces [3] [4] [5]. This paper outlines the super-elastic brace. Also described are structural test using super-elastic braces and an example of its application to an actual building.

2. Outline of super-elastic brace

2.1 Features of super-elastic brace

A cross-sectional perspective of a super-elastic brace is given in Fig. 1. A super-plastic brace is composed of three steel elements of different diameters (core, middle tube and outer tube from the inside). The three steel elements are connected traversability to each other to increase the actual length (2.5*L*) of the member to 2.5 times the apparent length (*L*).

The axial force-axial displacement relationship between the super-elastic brace and the conventional brace is shown in Fig. 2. In conventional braces, axial stiffness and axial strength increase in proportion to the cross-sectional area. Elastic limit displacement, which is determined by member length L and yield strain δ_y, does not change unless the material strength is increased. Special steel with a high material strength has such disadvantages as high cost and difficulty in quality control. Super-elastic braces have an actual member length 2.5 times (2.5*L*) as large as the apparent length. Then, elastic limit displacement increase 2.5 times. Thus, braces that would not yield at a story drift angle of less than 1/200 rad are realized.

From a structural viewpoint, axial forces of adjacent steel elements offset each other in compression and in tension, and as a result, buckling is controlled (Fig. 3). Super elastic braces operate stably even at large deformations of R = 1/100 rad or more [5].

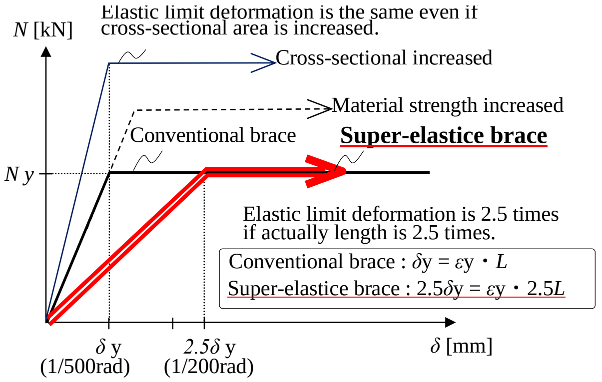


Fig. 2 – Axial force-axial deformation relationship

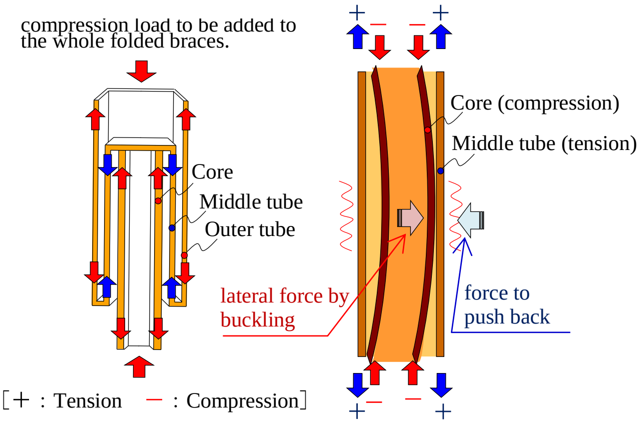


Fig. 3 – Image of buckling restriction effect

2.2 Effects of applying super-elastic braces

The effects of applying super-elastic braces (relationships between base shear coefficient *C* and story drift angle *R*) are shown in a schematic view (Fig. 4). Fig. a) and b) is "pure moment resisting frame structures" and "conventional brace structures", respectively. Also, Fig. c) is “super-elastic brace structures”.

a) Pure moment resisting frame structures

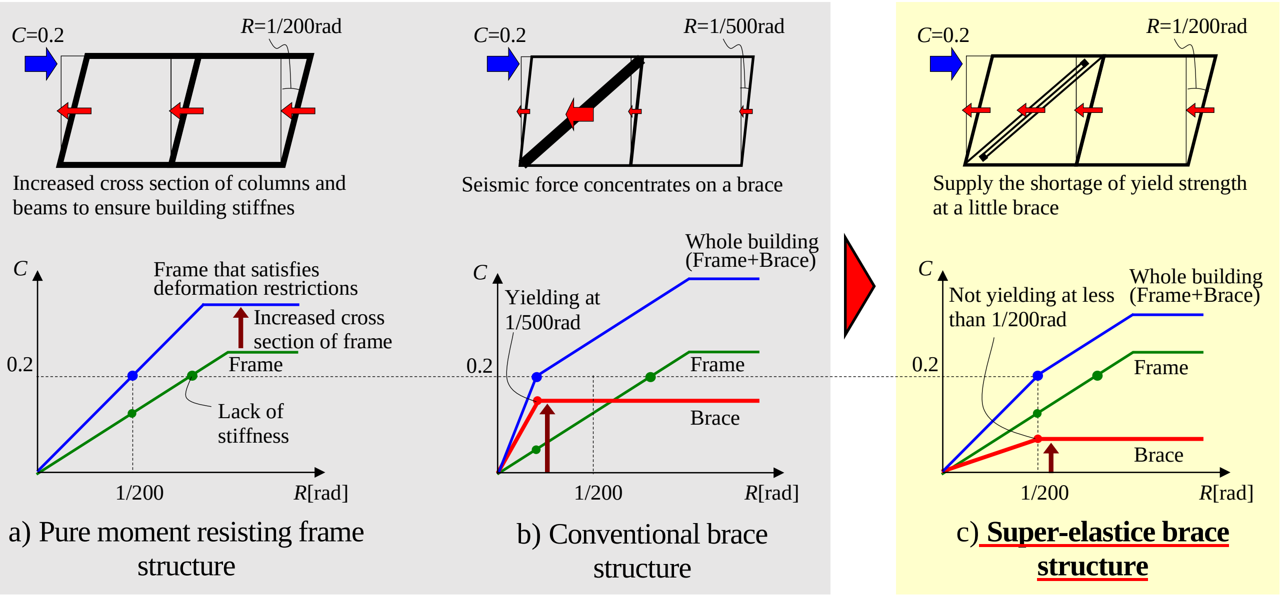
Pure moment resisting frame structure is soft and tenacious. However, even if it is sufficient in terms of yield strength, it is necessary to ensure building rigidity by increasing the cross section of the column beam excessively. This is due to the constraints of the first design that allow no yielding of members against a seismic force with *C* = 0.2 and hold story drift angle to 1/200 rad or smaller.

b) Conventional brace structures

The brace structure is economical because it can secure rigidity with less steel than the pure moment resisting frame structure. However, In the conventional brace structure, stiffness in the brace section is much greater than in the frame section and therefore most of the seismic forces concentrate in the brace. No frame strength becomes effective. Also, conventional braces yield due to small deformation (*R* = 1/500 rad). No braces can therefore be arranged in small numbers because of the restrictions in the first design.

c) Super-elastic brace structures

In the super-elastic brace structure, no brace yields until *R* reaches 1/200 rad. The shortages of strength and stiffness in the brace at the primary design level can be compensated for efficiently by a few braces. Then, a rational brace structure is realized that makes an effective use of frame strength. The degree of freedom increases for planning brace arrangement because no stress concentration occurs even where a few braces are arranged and because torsion has little effect in the case of eccentric arrangement.



a) Pure moment resisting frame structure

b) Conventional brace structure

c) **Super-elastice brace structure**

※*C* : Bass shear coefficient (The value that divided a story shear force of the first floor by total weight)

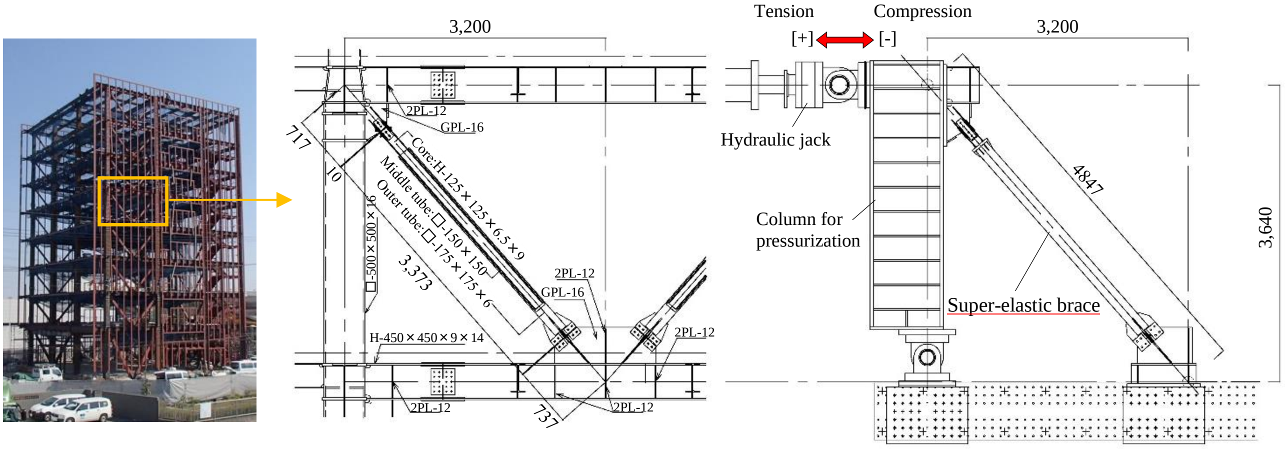
Fig. 4 – Application effect of the super-elastic brace
(Bass shear coefficient - Interstory drift angle relationship)

3. Structural test of super-elastic brace

This section describes a structural test conducted to verify the performance of super-elastic braces applied to an actual building [4].

3.1 Force application device and testing method

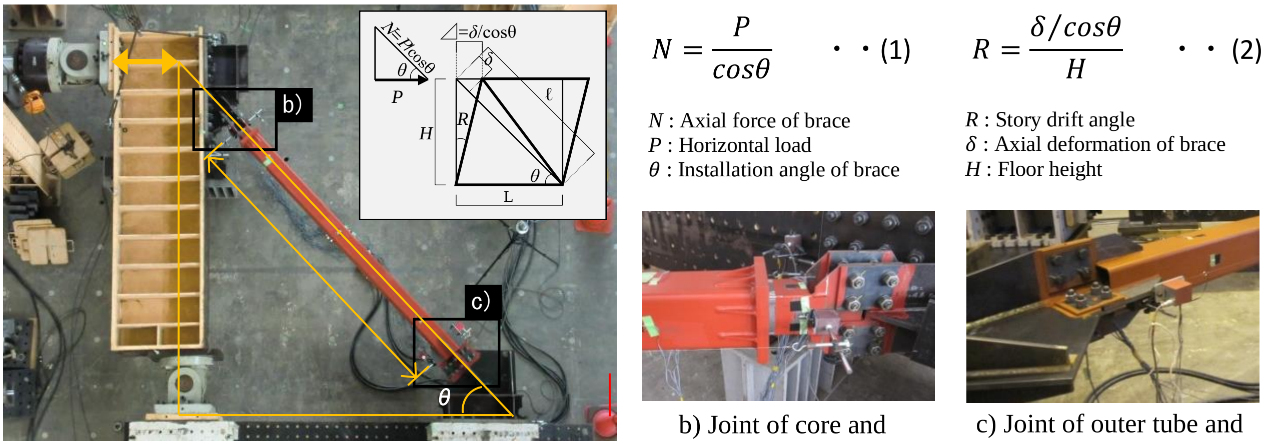
A photograph of the actual building, detailed plan of the frame and the loading device are shown in Fig. 5. The specimen was used as a super-elastic brace on the fifth floor of the eight-storied steel framed building described in Chapter 4. In the test, the floor height H (3.64 m), span l (3.2 m), angle of application and member for application were completely reproduced to verify the structural performance of the super-elastic brace embedded in the actual frame. Axial force was made to act through a loading column rotating around a pin axis at the foot.



a) Photo of frame b) Detail plan of frame c) Force application device

Fig. 5 – Frame on building and Force application device

How testing was conducted is shown in Fig. 6. Elements are connected by friction to each other at joints using high strength bolts as in the actual building. Strength 1.2 times the axial yield strength (N_y = 903 kN) was secured at joints for safety. Horizontal load P, axial displacement δ and axial strain of each steel bar were measured (Fig. 6). Axial force N was calculated from horizontal load P using equation (1). Story drift angle R was calculated from axial displacement δ using equation (2).



$$N = \frac{P}{\cos\theta} \quad \cdot\ \cdot\ (1)$$

N : Axial force of brace
P : Horizontal load
θ : Installation angle of brace

$$R = \frac{\delta/\cos\theta}{H} \quad \cdot\ \cdot\ (2)$$

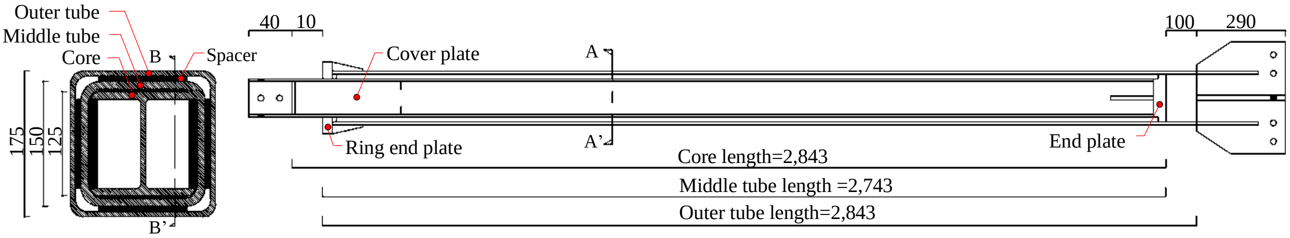
R : Story drift angle
δ : Axial deformation of brace
H : Floor height

a) Complete view b) Joint of core and frame c) Joint of outer tube and frame

Fig. 6 – Photo of experiment condition

3.2 Shape of specimen

The shape of the super-elastic brace used as the specimen is shown in Fig. 7. H-section steel was used for the core, and square-shaped steel pipes were used for the inner and outer tubes. The gaps between steel elements were filled with spacers [5]. In the exposed sections of the core, the cross-sectional performance was likely to be insufficient and breaking and buckling likely to occur [5]. Cover plates therefore were applied to increase strength.



a) Sectional view of A-A' b) Sectional view of B-B'

Fig. 7 – Shape of test specimen

The calculation value of yield axial force, axial stiffness and elastic limit displacement for the specimen are listed in Table 1. The table also shows the specifications for a conventional brace that solely used the core. The yield axial force of the super-elastic brace N_y was calculated using the minimum yield axial force of steel elements as expressed in equation (3). In the specimen, N_y was determined by the cross section of the core.

The axial stiffness of super-elastic brace K was calculated by combining in series the axial stiffness of respective steel (4). The elastic limit displacement of super-elastic brace δ_y was calculated using equation (5).

$$N_y = \min(N_{1y}, N_{2y}, N_{3y}) = N_{1y} \quad \cdot\cdot (3)$$

$$K = \frac{1}{(1/K_1) + (1/K_2) + (1/K_3)} \quad \cdot\cdot (4) \qquad \delta_y = \frac{N_y}{K} \quad \cdot\cdot (5)$$

N_y : Yield axial force of brace of Super-elastic brace
N_{1y} : Yield axial force of brace of Core
N_{2y} : Yield axial force of brace of Middle tube
N_{3y} : Yield axial force of brace of Outer tube

K : Axial stiffness of Super-elastic brace
K_1 : Axial stiffness of Core
K_2 : Axial stiffness of Middle tube
K_3 : Axial stiffness of Outer tube

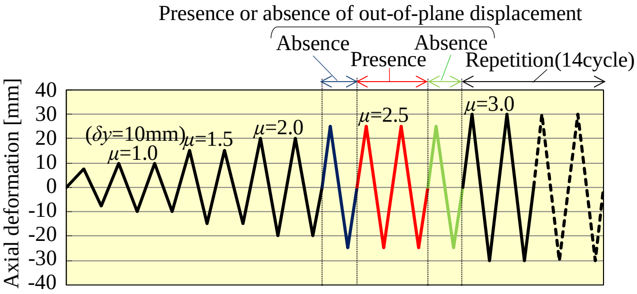
δ_y : Elastic limit deformation of Super-elastic brace

Table 1 – Principal specifications of test specimen

		Each member						Total			
		Geometries H-A×B×t_w×t_f □-A×B×t_w×t_f	Yield point	Cross section	Length	Yield axial force	Axial stiffness	Yield axial force N_y	Axial stiffness K	Elastic limit defor-mation δ_y	Story drift angle R_y
			[N/mm^2]	[mm^2]	[mm]	[kN]	[kN/mm]	[kN]	[kN/mm]	[mm]	[rad]
Super-elastic brace	Core	H-125×125×6.5×9.0	303	2,982	2,843	903	215	**903**	**91**	**9.91**	**1/243**
	Middle tube	□-150×150×9.0	416	4,798	2,743	1,996	359				
	Outer tube	□-175×175×6.0	348	3,932	2,843	1,368	284				
Conventional brace (Core only)		H-125×125×6.5×9.0	303	2,982	2,943	903	208	903	208	4.35	1/553

3.3 Loading cycles of test

Loading cycles are shown in Fig. 8. Loads were applied by alternate loading and unloading while controlling displacement based on the elastic limit displacement $\delta_y = 10$ mm ($\mu = 1.0$). First, two cycles of loading were applied each at $\mu = 1.0$ and 1.5. Then, one cycle of loading was applied at $\mu = 2.0$. Two cycles were applied while forced out-of-plane deformation was given equivalent to an interstory drift angle R of 1/100 rad and another was applied while there was no out-of-plane deformation. Subsequently, loading was repeated at $\mu = 3.0$ until the specimen failed. Loading in tension was considered positive. Major structural performance features of super-elastic braces expected during design are listed Table 2.



※μ : Plasticity rate (The value that divided axis displacement by elastic limit displacement)

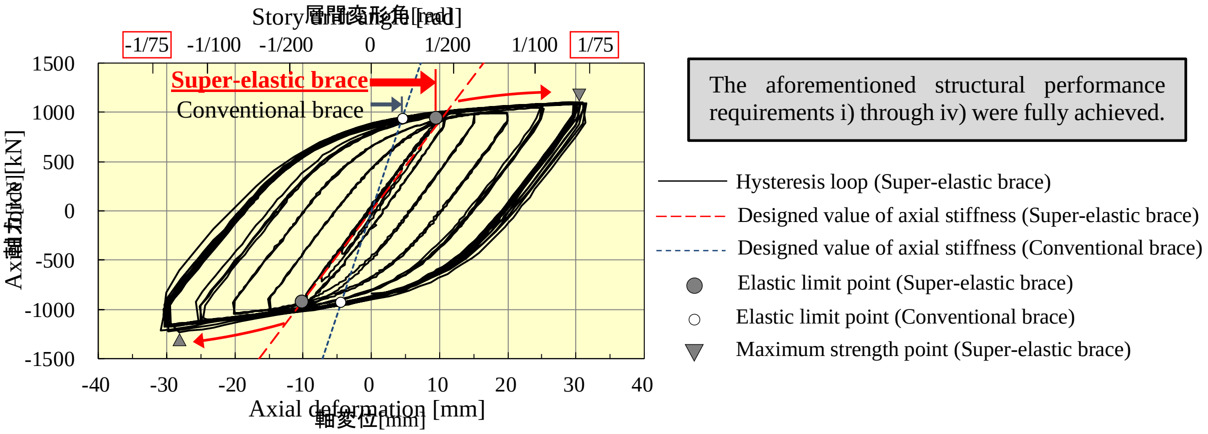
Fig. 8 – Loading cycle

Table 2 – Main structural performance of super-elastic brace

i)	Elastic limit displacement increases in proportion to member length.
ii)	Axial stiffness can be calculated using equation (4) shown below.
iii)	Compressive strength equivalent to tensile strength is realized owing to the effect of controlling buckling.
iv)	Super elastic braces operate stably even at large deformations of R = 1/100 rad or more.

3.4 Test results (Axial force-axial displacement relationship)

The relationships between axial force and axial displacement obtained of all cycles of loading in the test are shown in Fig. 9. The figure also shows designed values of axial stiffness of super-elastic and conventional braces. The figure shows that experimental values of axial stiffness were nearly in agreement with calculated values. The elastic limit displacement of super-elastic brace was approximately 2.3 times that of conventional braces. The compressive strength of super-elastic brace was equivalent to tensile strength. Also, the figure shows no significant difference in the hysteresis loop whether there was out-of-plane deformation equivalent to R = 1/100 rad or not. In addition, stable spindle-shaped hysteresis loops were exhibited even after the repetition of numerous great deformations at μ = 3.0 (equivalent to R = 1/75 rad). It is therefore evident that the aforementioned structural performance requirements i) through iv) were fully achieved. In the end, sliding occurred at a joint where elements were connected by friction to each other using high strength bolts, at the peak of compression in the 14th cycle of repeated loading at μ = 3.0. Then, the test was terminated.



The aforementioned structural performance requirements i) through iv) were fully achieved.

Fig. 9 – Axial force-axial deformation relationship

4. Example of application in an actual building

This section describes an example of application of super-elastic braces in an eight-storied newly constructed steel framed office building [5].

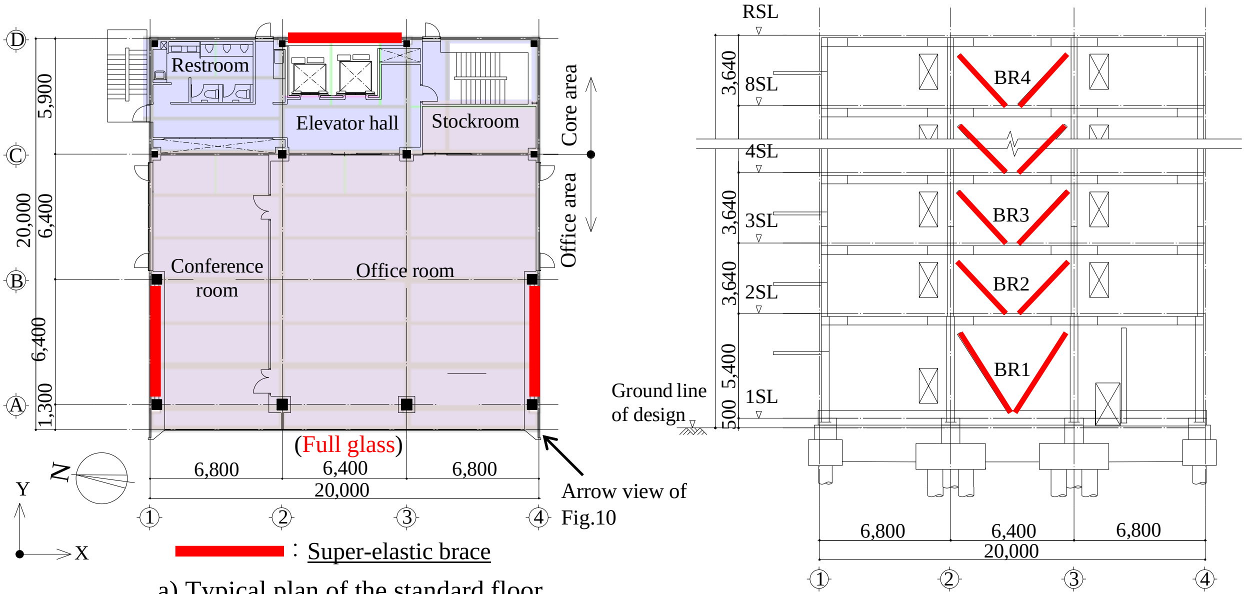
4.1 Building outline and structural plans

Basic data on the building are shown in Table 3. A photograph of the exterior are shown in Fig. 10. Also, a plan view and an elevation view are shown in Fig. 11. Fig. 11 shows the positions of super-elastic braces applied. The positions of braces are frequently restricted by the appearance or functions of the building. The building in which braces were applied also had numerous restrictions. There were a few positions where braces could be arranged either in the X or Y direction. In the X direction, braces were applied eccentrically only at one position. The brace structure may have been abandoned and the pure rigid frame structure adopted for the building because of stress concentration and torsion. Adopting super-elastic braces, however, enabled brace arrangement that may not have been realized using conventional brace structures.

Table 3 – Basic building data

Structure classification	Steel structure
Use	Office building
Number of floors	8 floors above ground
Floor height of the standard floor	3.64m
Eaves height	31.38m
Total floor area	3,267m^2
Total weight for seismic design	21,718kN

Fig. 10 – Photograph of exterior



a) Typical plan of the standard floor

b) Framing elevation (D-Dir.)

Fig. 11 – Position of Super-elastic brace

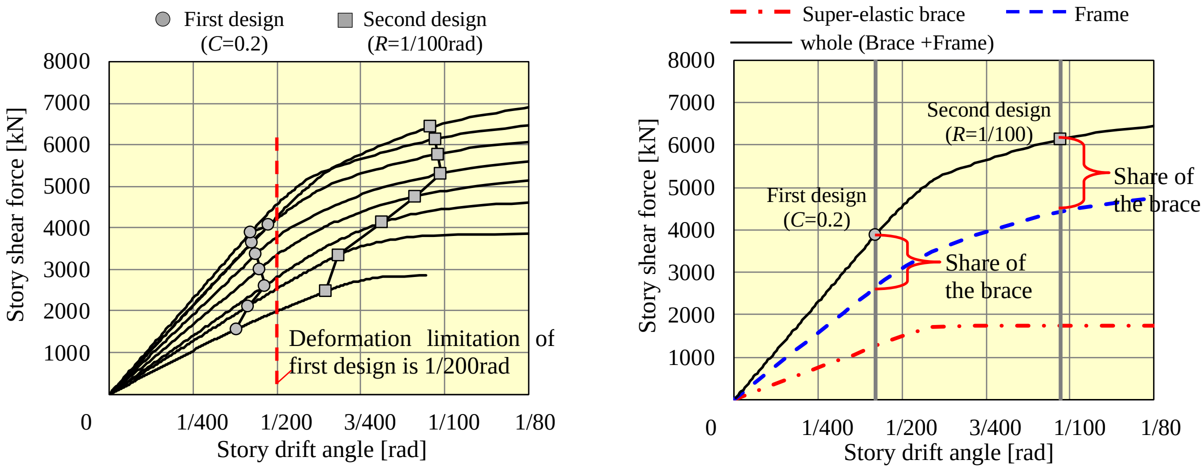
4.2 Structural performance of the entire building (results of analysis in X direction)

This section describes the results of incremental load analysis in the X direction in which braces were arranged eccentrically.

Relationship between story shear force Q and story drift angle R are shown in Fig. 12. Fig. a) shows the results for the entire building. Fig. b) separately shows the relationships for the frame and super-elastic braces on the second floor. No super-elastic brace yielded until the story drift angle reached approximately 1/200 rad. Then, the strength of the frame was effective from the time of first design (C = 0.2). Strength and stiffness that could not be provided solely by the frame were efficiently compensated for by super-elastic braces.

In the building, the lateral force shared by braces was set at approximately 20% at the time of first design (C = 0.2) to prevent braces from carrying excessive forces, from consideration for eccentricity and support reaction (Table 4).

Fig. 13 shows story drift angle on each floor at the center of gravity, node along line A and node along line D (where braces were applied) at the times of first design (C = 0.2) and secondary design (R = 1/100 rad). In the X direction, few effects of torsion were found at the time of first design although braces were arranged eccentrically. At the time of secondary design, the difference in displacement was slightly larger. The difference was, however, approximately 10% and had little effect.



a) The whole building

b) Second floor

Fig. 12 – Story shear force - Story drift angle relationship

Table 4 – Ratio of story shear force of

No. of floors	First design (C=0.2)		Second design (R=1/100rad)	
	Frame	Brace	Frame	Brace
8F	83.0	17.0	82.4	17.6
7F	80.2	19.8	80.4	19.6
6F	79.2	20.8	78.0	22.0
5F	80.0	20.0	78.7	21.3
4F	76.0	24.0	74.8	25.2
3F	75.7	24.3	76.7	23.3
2F	67.8	32.2	71.8	28.2
1F	72.7	27.3	76.9	23.1

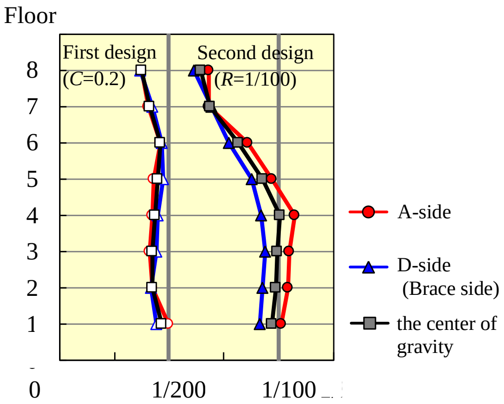


Fig. 13 – Story drift angle of each node

4.3 Comparison in the total amount of steel

In order to verify the effectiveness of super-elastic braces, a pure moment resisting frame structures with an equivalent seismic resistance was designed. A comparison in the total amount of steel between super-elastic brace structures and pure moment resisting frame structures is shown in Fig. 14. The total amount of steel was approximately 20% smaller in super-elastic brace structure than in pure rigid frame structure. In buildings where the application of brace structure is abandoned because of stress concentration or torsion, a rational brace structure can be realized using super-elastic braces and the total amount of steel can be reduced.

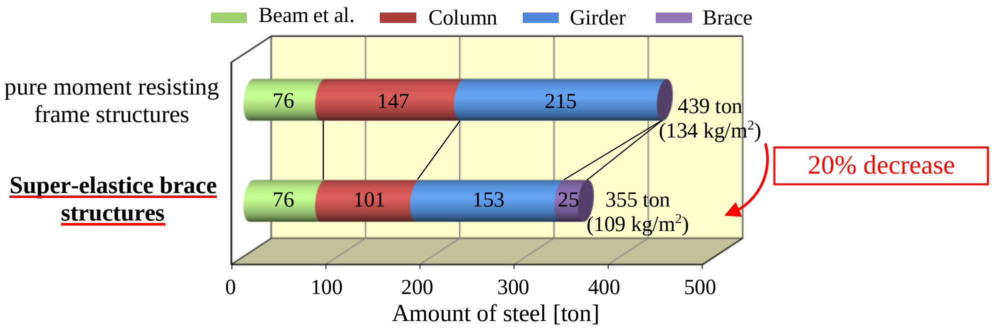
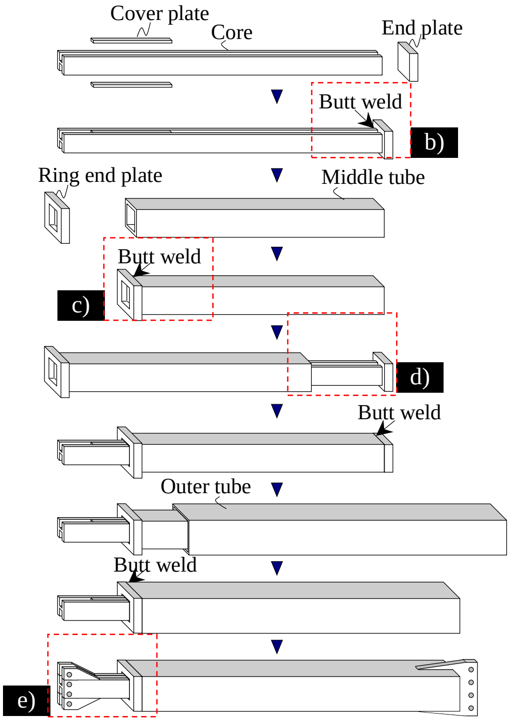


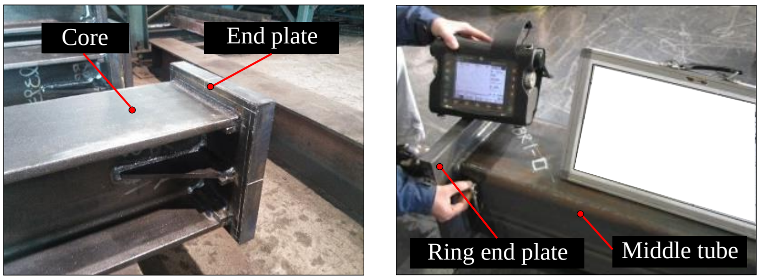
Fig. 14 – Comparison of the total amount of steel

4.4 Production of super-elastic brace

A procedure for producing a super-elastic brace is shown in Fig. 15. The core and middle tube are connected via an end plate. The middle and outer tubes are connected v ia a ring-shaped end plate. Super-elastic braces can be produced in compliance with normal management standards without using any special steel or welding method [6].

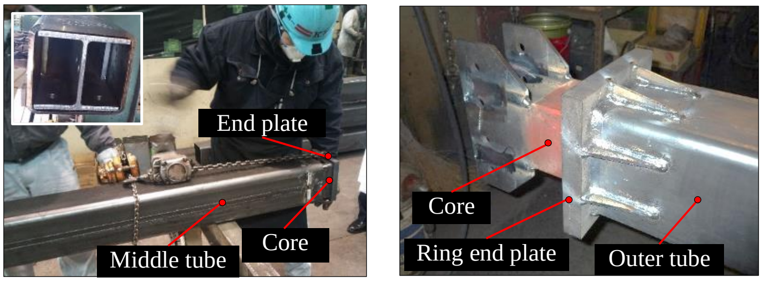


a) Production procedure



b) Butt welding status of core and end plate

c) Butt welding status of middle tube and ring end plate



d) Insertion of core into middle tube

e) Butt welding status of outer tube and ring end plate

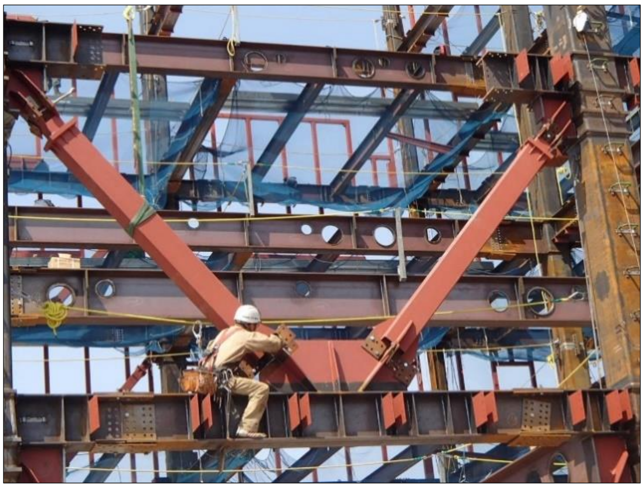
Fig. 15 – Production procedure of the Super-elastic brace

4.5 Construction of super-elastic brace

How super-elastic braces are constructed is shown in Fig. 16. Elements are connected to each other at joints using high strength bolts as in conventional braces. No special erection method is required and therefore construction is easy [7].

a) Shipment situation of brace b) Joint of core and frame c) Joint of outer tube and frame

e) Construction status (full view)



d) Construction status (full view) f) Construction status (details)

Fig. 16 – Construction status of super-elastic braces

5. Conclusion

This paper outlined the super-elastic brace and presented a structural test of super-elastic brace. Also described was an example of its application in an actual building. The conclusions of this paper are described below.

1) Chapter 2 outlined the super-elastic brace. In the super-elastic brace, three steel elements are folded traversability and connected to one another to increase the actual length of the member to 2.5 times the apparent length. Increasing the member length realizes a brace that would not yield at an story drift angle of less than 1/200 rad.
2) Chapter 3 described a structural test for super-elastic braces. Loading tests were conducted using a super-elastic brace used in an actual building. As a result, it was verified that the super-elastic brace had high structural performance as expected in design.
3) Chapter 4 describes an example of application of super-elastic braces in an actual building. In buildings where adopting the brace structure would have been abandoned for design reasons, using super-elastic braces realizes a rational brace structure and the total amount of steel could be reduced by 20%. From a construction viewpoint, it was confirmed that no special production and erection methods are required for super-elastic braces and that construction is easy.

6. Acknowledgements

Those concerned provided numerous advices and cooperation in research and development and practical application concerning super-elastic braces, a new technology. The authors would express their gratitude to all those concerned.

7. References

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