

# Ultra High Strength Steel for Sustainable Building Structures

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## Abstract

*Sustainability of building structures is focused on especially after the Hanshin-Awaji earthquake in 1995. Nippon Steel & Sumitomo Metal Corporation developed the minimum yield strength of 700 N/mm<sup>2</sup> and the minimum yield strength of 880 N/mm<sup>2</sup> steel for the columns used in advanced damage control design, and put them into the first practical use in the world.*

## 1. Introduction

In Japan, known worldwide as a country often hit by earthquakes, desirable building structures with good weldability and economic efficiency have been pursued with efforts of learning lessons from the past disasters of big earthquakes. In recent years, building structures, not only preventing collapse, but enables reuse even after earthquake without losing their original function have been sought for. For such occasions, High strength steel with large elastic region has been focused on.

Based on the vast experience in the production of high-strength steel, Nippon Steel & Sumitomo Metal Corporation has developed steel up to 880 N/mm<sup>2</sup> yield strength class (tensile strength 1 000 N/mm<sup>2</sup>) having excellent weldability and economy for the building structures designed with advanced earthquake-resistant design concept, and put them into practical use. This article reports the development guide line, mechanical properties, and examples of actual application of the ultrahigh strength steel above 700 N/mm<sup>2</sup> yield strength class (tensile strength, 780 mm<sup>2</sup>).

## 2. Earthquake-Resistant Design and Trend in Steel Material for Building Use

In recent years, based on the new earthquake-resistant design method introduced in 1981 at the time of revision of the Building Standards Act, building structures have been designed to enclose the deformation of a framework to its elastic regions for medium scale earthquake, and for large scale earthquake which may encounter only once in its service life, building structure have been designed to absorb seismic energy through the plastic deformation of their framework.

However, for the purpose of effective utilization of land, with the construction of more high-rise building structures, heavier steel

plates and higher strength steel are required for use in steel frame works. To comply with the requirement, thermo-mechanical control process (TMCP) steel yield strength (YS) 325 N/mm<sup>2</sup>, YS 355 N/mm<sup>2</sup> for plates in the thickness range of up to 100 mm was developed for building structures by applying TMCP; they have been used since the latter half of the 1980s subject to acquisition of recognition of the Minister of Construction at the time.

During the same period, research on enhancing the reliability of plastic deformation capability of a frame work was advanced, and in 1994, during the enactment of a standard for rolled steel material for building structural use (SN) in the Japanese Industrial Standard (JIS), yield ratio and upper criterion of yield strength were specified for the TMCP steel for building structures and these standards were employed extensively for high-rise buildings in particular.

In the Hanshin Awaji Great Disaster in 1995, although many building suffered huge casualties, the damage to the buildings designed in compliance with the new earthquake-resistant design method was relatively less serious. However, even though a building could prevent a collapse, thanks to large plastic deformation as originally designed, the continued use of the building was accompanied with difficulties; therefore, these buildings suffered a loss of asset value. To avoid such situation, new design method which enclose the deformation of a framework to its elastic regions instead of plastic deformation of other members for absorption of seismic energy was studied. In order to realize such a design or "Elastic design for seismic intensity 7," which far exceeds the seismic capability of the past, the "Development of new structural system using novel structural material" was started with the cooperation of government departments and the development of new structural design for excellent aseismic performance were advanced.

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3. Ultrahigh Strength Steel Plate of Nippon Steel & Sumitomo Metal for Building Structure Use

To ultra high-rise building structures built on the new design concept, damage control design is applied, which controls the damage to columns and beams by employing a seismic energy absorption mechanism termed as damper to enable the reuse of the building even after an earthquake (Fig. 1 (b))<sup>1)</sup>. For the effective functioning of such a mechanism, the following steels are used. For dampers, low-yield strength steel with large elongation; for beams, steel guaranteed for plastic deformability with controlled yield strength and yield ratio; and for columns, steel having higher yield strength than that of beams. Nippon Steel & Sumitomo Metal has already commercialized BT-HT400 and BT-HT500, which have higher yield strength than that of conventional steel for columnar steel material, and furthermore, has tackled the problem of the development of high-strength steel for columns, which enables dampers to absorb seismic energy more effectively by reducing the section area of column. Nippon Steel & Sumitomo Metal has also commercialized BT-HT700 and BT-HT880 in which the lower criterion of yield strength was set at 700 N/mm<sup>2</sup> and 880 N/mm<sup>2</sup>, respectively.

Nippon Steel & Sumitomo Metal caters to the requirements of improving weldability by lowering the weld crack sensitivity index ( $P_{CM}$ )<sup>2,3)</sup> which is realized by using sophisticated TMCP technology. This technology allows the elimination of preheating or lowering of preheating temperature and enhancing welded joint toughness us-

ing high HAZ toughness with fine microstructure imparted by fine particles (HTUFF™)<sup>4,5)</sup> for refining grain size. Moreover, a series of steel material, as shown in Fig. 2, has been established to comply with the demand of earthquake-resistant design of ever-growing sophistication: (1) BT-LYP100, 225, low-yield strength steel material for seismic energy absorbing members, (2) BT-HT325, 385, 440, and 630, conventional low-yield-ratio-type steel material, and (3) BT-HT400, 500, 700, and 880, in addition to the abovementioned series, high-yield strength steel material with large elastic region.

4. Characteristics of BT-HT700 and BT-HT880

4.1 Standard of steel material

Table 1 shows the steel material standard of BT-HT700 and BT-HT880. The standard specifies minimum yield strength as 700 N/mm<sup>2</sup> and 880 N/mm<sup>2</sup>, respectively, and the yield ratio as 98% from the viewpoint of utilizing the elastic region to the maximum extent possible, while securing post-yielding complementary strain energy. Furthermore, as for BT-HT700, another specification of Charpy impact test value at the test temperature of -20°C was set for circular sectioned steel pipe columns.

4.2 Mechanical properties of BT-HT700 and application to practical use

4.2.1 Mechanical properties of steel material

Table 2 shows the chemical compositions of test samples. A composition system of low carbon with low  $P_{CM}$  was employed for the purpose of enhancing weldability. Furthermore, optimization of hardenability with the addition of Ni, Cr, Mo, B, etc., and the reduction of the impurities of P and S were conducted to stabilize fracture toughness. Table 3 shows the result of y-groove cracking test. It

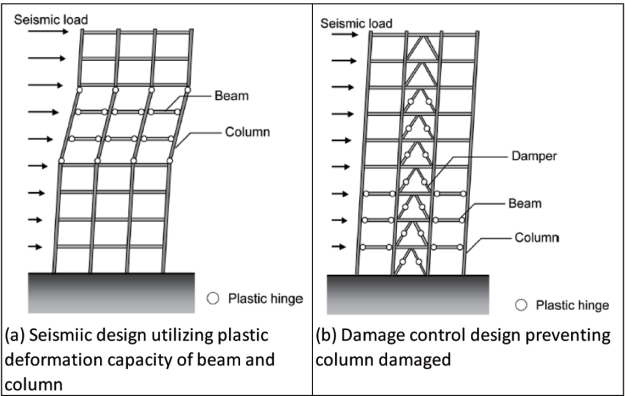


Fig. 1 Schematic illustration of seismic design concept<sup>1)</sup>

Table 1 Material specification

Brand name	Tensile test			Charpy impact test (1/4t, L-dir.)	
	YS (N/mm <sup>2</sup> )	TS (N/mm <sup>2</sup> )	YR (%)	Test temperature (°C)	Absorbed energy (J)
BT-HT700	700–900	780–1 000	≤ 98	0	≥ 47
				-20	≥ 47
BT-HT880	880–1 060	950–1 130	≤ 98	0	≥ 70

t: Thickness, L-dir.: Longitudinal direction

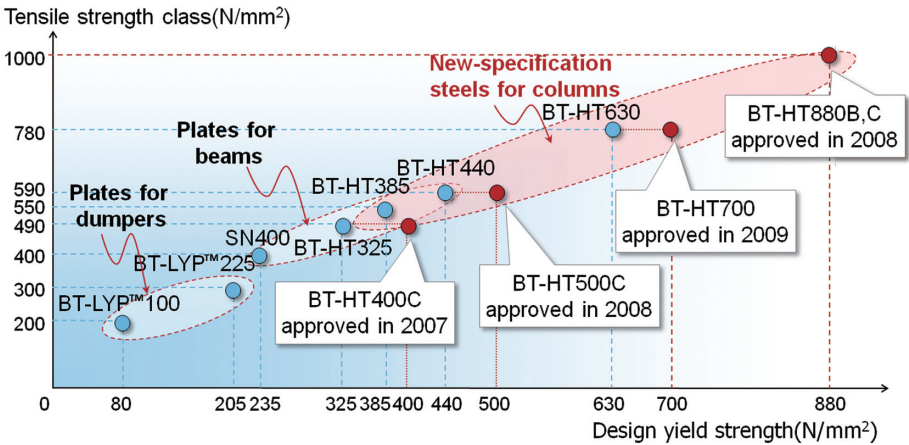


Fig. 2 Nippon Steel & Sumitomo Metal's steel plate used for building structure

was confirmed that low-temperature cracking was not developed on the steel material even without preheating. **Table 4** shows the results of the tensile test and Charpy impact test. High strength and stable Charpy impact properties are secured. Assuming that the steel material is used for circular-sectioned steel pipe columns, mechanical properties before and after cold bending was assessed, and the test results are shown in **Table 5**. Stable strength and Charpy impact properties are exhibited and confirmed even after forming to pipe, and it was judged that the steel material can also be used for steel pipe columns.

#### 4.2.2 Examples of application to practical use

In the main building of Obayashi Corporation's Technical Research Institute, known as "Techno Station" (**Fig. 3**), BT-HT700 steel plate of 25 mm thickness was used for high strength, concrete-filled steel pipe (CFT) for the first time in the world. By taking advantage of its characteristics of BT-HT700 steel plate such as the yield strength, which is twice that of conventional steel material

**Table 2 Chemical compositions (mass%)**

C	Si	Mn	P	S	Others	Ceq	P <sub>CM</sub>
0.07	0.06	1.24	0.008	0.001	Cu, Ni, Cr, Mo, Nb, Ti, B	0.58	0.22

$$Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14$$

$$P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B$$

**Table 3 Result of y-groove cracking test (60 mm thickness plate)**

Welding condition	Atmosphere	Preheat temperature	Crack ratio
GMAW (CO <sub>2</sub> ) YM-80C, 1.7kJ/mm	20°C, humidity 60%	Free	0%

GMAW: Gas metal arc welding

**Table 4 Mechanical test results (25 mm thickness plate)**

Thickness position	Tensile test (JIS5B, Flat, T-dir.)			Charpy impact test (1/4t, L-dir.)	
	YS (N/mm <sup>2</sup> )	TS (N/mm <sup>2</sup> )	YR (%)	Test temperature (°C)	Absorbed energy (J)
Full-thickness	801	852	94	-20	324
Target (BT-HT700B)	700-900	780-1 000	≤ 98	-20	≥ 47

T-dir.: Transverse direction

**Table 5 Mechanical properties of pipes (25 mm thickness plate, cold forming, thickness/diameter=0.05)**

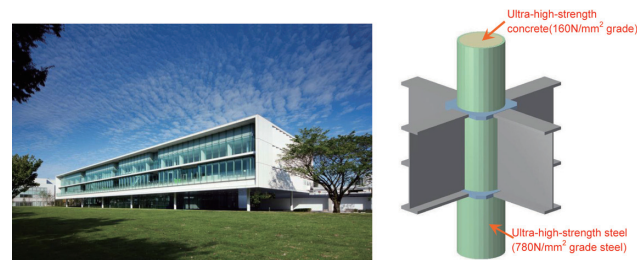
Tested sample	Direction	Tensile test (full-thickness)			Charpy impact test (1/4t, L-dir.)	
		YS (N/mm <sup>2</sup> )	TS (N/mm <sup>2</sup> )	YR (%)	Test temp. (°C)	Absorbed energy (J)
Plate	L	788	842	94	-20	302
Pipe (as formed)	Pipe axial (L-dir. of plate)	801	879	91	-20	281

(SM490A) and the P<sub>CM</sub>, which is lower as compared with that of the conventional 700 N/mm<sup>2</sup> yield strength class steel, both reduction of wall thickness and good weldability are ensured. Furthermore, the reduction of columnar diameter was achieved owing to enhanced filling concrete strength, improved fire-resistant coating, etc. Furthermore, an open space with a long span and a stairwell with fire resistance in addition to high earthquake resistance capability has been simultaneously realized (**Fig. 4**).<sup>6)</sup> Furthermore, by using these high-strength materials, the amount of steel material and concrete can be saved, which relieves environmental load.

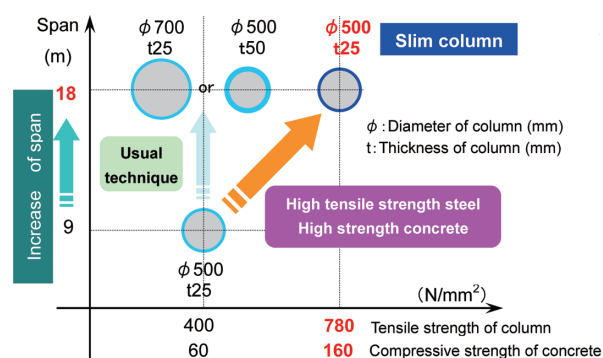
### 4.3 Mechanical properties of BT-HT880 and application to practical use

#### 4.3.1 Mechanical properties of steel material

**Table 6** shows the chemical compositions of test samples. Similar to that of BT-HT700, chemical composition was designed with low carbon and low P<sub>CM</sub> system to ensure good weldability. To obtain the compatibility of high-strength and excellent toughness, alloy designing and heat treatment conditions were optimized, which aimed at tempered fine martensitic microstructure. **Table 7** shows the results of the mechanical property tests of the steel material. It is known that the uniform strength and stable Charpy impact properties are secured throughout the thickness of a 50-mm-thick heavy steel plate. As shown in **Fig. 5**,<sup>7)</sup> the characteristic nature of the steel is that the steel has larger elastic region than that of the generally used 490 N/mm<sup>2</sup> tensile strength class steel and exhibits sufficient



**Fig. 3 Appearance of Obayashi Corporation's Technical Research Institute Main Building "Techno-Station" and column applied BT-HT700 (photo and figure provided by Obayashi Corporation)**



**Fig. 4 Feature of ultra-high-strength CFT column**

**Table 6 Chemical compositions (mass%)**

	C	Si	Mn	P	S	Others	Ceq	P <sub>CM</sub>
Ladle analysis	0.10	0.19	0.97	0.005	0.001	Cu, Ni, Cr, Mo, V, Nb, Ti, B	0.54	0.26

Table 7 Mechanical test results (50 mm thickness plate)

Thickness position	Dir.	Tensile test (JIS4 round type)				Charpy impact test (1/4t, L-dir.)	
		YS (N/mm <sup>2</sup> )	TS (N/mm <sup>2</sup> )	YR (%)	El (%)	Test temp. (°C)	Absorbed energy (J)
1/4t	T	909	966	94	23	0	279
1/2t	T	892	962	93	21	0	242
Target		880–1 060	950–1 130	≤98	≥13	0	≥70

T: transverse

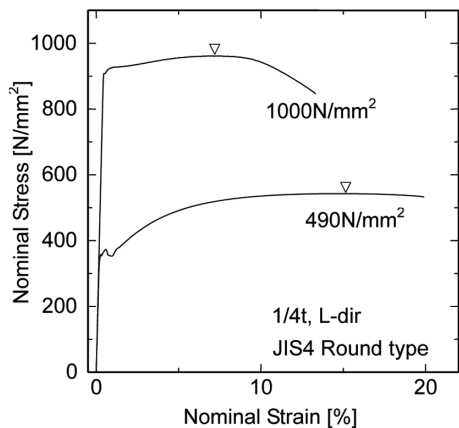


Fig. 5 Stress strain curve

Table 8 Result of y-groove cracking test (50 mm thickness plate)

Welding condition	Atmosphere	Preheat temperature	Crack ratio
GMAW (95%Ar + CO <sub>2</sub> ) YM-100AS, 17 kJ/cm	35°C, humidity 48%	100°C	0%

elongation even after yielding. **Table 8** shows the results of the weldability test. The steel material has the ability to suppress low temperature cracking with preheating at 100°C.

4.3.2 Examples of application to practical use

Amagasaki R&D Center of Nippon Steel & Sumitomo Metal is introduced as an example of the practical use of BT-HT880.<sup>7,8)</sup> A yield strength of 880 N/mm<sup>2</sup> steel was applied to this building for the first time in the world. In 2008, the recognition from the Minister of Land, Infrastructure and Transport was acquired for the following: steel material, welding material, welding work conditions, and basic guide line of structural designing. Moreover, in 2012, the building was completed.

BT-HT880 was used for the columns on the first floor intended for enlarging the elastic criterion at the time of an earthquake and earthquake energy dissipative braces were arranged intensively (**Figs. 6, 7**). The building is designed in a way such that it absorbs the majority of the seismic energy input to the building effectively on the first floor section and controls the deformation of the column and beam materials to within elastic criterion even in a major earthquake. To build a large space with a beam span length of 23 m, a column has to withstand a major load. Reduction of the sectional area of a column was realized using BT-HT880 for the columnar

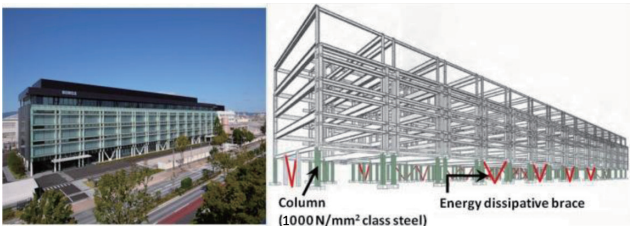


Fig. 6 Appearance of Amagasaki Research and Development Center, and application part of BT-HT880 steel plate<sup>3)</sup>



Fig. 7 Appearance of energy dissipative brace and column applied BT-HT880

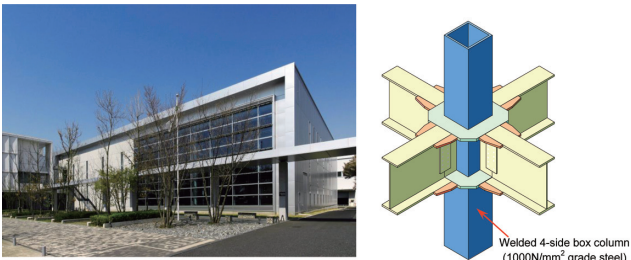


Fig. 8 Appearance of Obayashi Corporation's Technical Research Institute "Multipurpose Laboratory 2", and column applied BT-HT880 (photo and figure provided by Obayashi Corporation)

material and by fabricating a single column with two columns combined together. Furthermore, newly developed submerged arc welding material of 1 000 N/mm<sup>2</sup> tensile strength class was used for the welding of flange/web of the welded built-up H beam (BH) to be used as a column.<sup>9)</sup> In the welding of high strength steel, preventive measures for weld metal cracking are important in particular for securing strength and toughness of welded joints. Preheating temperature, welding heat input, inter-weld-pass temperature, post heating condition in multilayer welding, etc., were studied in detail. Consequently, a welding condition could be found wherein the desired throat thickness is obtained with only one pass and without causing welding cracking and, in actual welding work, no post heating was needed.<sup>10)</sup>

In Obayashi Corporation's Technical Research Institute Open Laboratory 2, external diaphragm-type four-side-welded box type column of BT-HT880 was employed (**Fig. 8**). Four-side-welded box is of a common type columnar cross-sectional figure generally employed in office buildings, which is similar to BH column. In this building, post heating was applied to the multilayer welding of the corners of the four-side-welded box type column based on the aforementioned study, and flawless welding for appearance, internal quality, and mechanical properties was realized.<sup>11)</sup>



## 5. Conclusion

To comply with the requirements of damage control design of building structures, BT-HT700 and BT-HT880, which have enhanced weldability and economy, have been developed and were used for the first time in the world for circular steel pipe columns, BH columns, and four-side-welded-box-type columns of domestic projects.

The ultrahigh strength steel of yield strength with 700 N/mm<sup>2</sup> or above is the steel material which makes building structure sustainable through the enhancement of seismic capacity. And further, it creates comfortable space with long span, in combination with the structural design that exploits the characteristic nature of the steel with large elastic region to the maximum extent possible. Therefore, expansion in application is expected in future.

## References

- 1) Suzuki, T., Suzuki, Y., Yoshida, Kubota, Shimura, Nagata: Nippon Steel Technical Report. (97), 71 (2008)
- 2) Tokuno, Okamura, Tanaka, Seto, Koyama, Yamashita, Iesawa, Fukasawa: Nippon Steel Technical Report. (75), 43 (1997)
- 3) Watanabe, Ishibashi, Yoshii, Inoue, Yoshida: Nippon Steel Technical Report. (90), 53 (2004)
- 4) Kojima, Kiyose, Uemori, Minagawa, Hoshino, Nakashima, Ishida, Yasui: Nippon Steel Technical Report. (90), 2 (2004)
- 5) Kojima, Yoshii, Hada, Saeki, Ichikawa, Yoshida, Shimura, Azuma: Nippon Steel Technical Report. (90), 34 (2004)
- 6) Suzui, Niwa, Fuchita, Tokinoya, Yamanaka, Endo: Report of Obayashi Corporation Technical Research Institute. (74), (2010)
- 7) Kawabata, Fukuda, Sasaki, Ichinohe, Shirasawa, Jinsenji, Yoshizawa, Taga, Fukusho, Kawai, Numata, Hashida: The Structural Technology. 24 (278), (2011)
- 8) Sasaki, Ichinohe, Nishio, Numata, Hashida, Kohzu, Tada, Kuwabara, Taga: Summaries of Technical Papers of Annual Meeting Architectural Institute of Japan. C-1, Structure III. 2007-05, p. 889
- 9) Kawabata, Ichinohe, Fukuda, Sasaki, Numata, Hashida, Fujihira, Kohzu, Tada, Kuwahara, Taga: Japan Welding Society Quarterly Journal. 29 (2), (2011)
- 10) Nakano, Numata, Okamoto, Yonemoto, Hashida: Katayama Technical Report. (32), (2013)
- 11) Suzui, Tokinoya, Niwa, Yamanaka, Nakatsuka, Okada: Report of Obayashi Corporation Technical Research Institute. (77), (2013)



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