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Development of High Performance and High Strength Steel Plates for Columns in Building Construction

Hiroshi ITO*
Yusuke SUZUKI
Masato NIKAIDO
Haruhiko NAKAGAWA
Itaru SUZUKI
Masaki ARITA
Tomoki URAKAWA

Abstract

Large and stocky section steel columns are typically used in steel buildings due to progressively increasing height and large spans. Nippon Steel Corporation has developed various high performance and high strength steel products in an attempt to enhance welding productivity in steel fabrication and control the total weight of the steel construction. This paper describes the recently developed 550 and 590 N/mm² class TMCP steel plate products for built-up box section columns and cold press-formed hollow square section columns.

1. Introduction

The construction of large-scale buildings, including superhigh-rise buildings, began in the 1960s in Japan. To meet the economic rationality and productivity needs of such buildings, Nippon Steel Corporation has developed and commercialized building structure steels and their joining and utilization technologies. In recent years, many large-scale redevelopment projects like superhigh-rise buildings have been implemented, mainly in the Tokyo metropolitan area. As steel frame buildings increase in height and size, the external loads assumed in the design stage increase. Consequently, primary structural frame members, or columns and beams, have become larger and thicker. Furthermore, high-strength steels with a large elastic deformation range are attracting attention not only from the standpoint of preventing the collapse of building structures under large earthquakes but also from the standpoint of continuously using buildings with their functions maintained after an earthquake. To enhance the cost competitiveness of steel frame members based on these needs, the strengthening of steels and rationalization of welding operations have become important issues in the steel structure.[1, 2] Against this background, Nippon Steel has made use of its abundant high-strength and high-performance steel production records and has developed high-strength construction steel plates that achieve both weldability and economy and cold press-formed steel hollow square sections (HSSs) made from such steel plates. In this paper, we present the trends and product lineup of steel plates for building structures. As recent development examples, we introduce 550 and 590 N/mm² grade TMCP steel plates for high heat input welding and 590 N/mm² grade TMCP cold press-formed HSSs.

2. Product Lineup of High Strength Steel Plates and High-Performance Cold Press-Formed HSSs for Buildings

2.1 Trends in steel plates for building structures

A new seismic design method was introduced when the Building Standard Law was revised in 1981. Based on the new seismic design method, buildings have been designed to maintain the frames in the elastic deformation range against medium-scale earthquakes and to absorb seismic energy by inelastic deformaiton of the frames during large earthquakes that may be encountered once during the service life of the building. As building structures become taller and larger, there is a growing demand for thicker and stronger steel plates to be used in the frames. In the latter half of the 1980s, the thermomechanical control process (TMCP) was adopted to commercialize 490 and 520 N/mm² grade tensile strength TMCP steels for building structures by keeping a certain yield strength up to a plate thickness of 100 mm and by keeping the carbon equivalent C_{eq} and weld crack susceptibility composition P_{CM} low to secure good weldability. In the 1990s, research was conducted to improve the reliability of the plastic deformation capacity of frames. When JIS G 3136 was established as the standard for rolled steels for building structures (SN) and with performance as seismic steels, the upper limits of yield ratio and yield strength were also set for TMCP steels

* Chief Manager, Head of Section, Dr.(Eng.), Building Products Engineering Section, Construction Products Engineering Dept., Osaka Office
4-5-33 Kitahama, Chuo-ku, Osaka City, Osaka Pref. 541-0041

for building structures. High-performance 590 N/mm^2 building structure steels (SA440) were also commercialized by matching their concepts with those of the SN standard and are now mostly used in superhigh-rise buildings. In the late 1990s, 780 N/mm^2 steels for building structures and based on the same idea as that of SA440 were commercialized and used in actual building projects.[3, 4] Since the 2000s, in response to the increasing needs for the quality improvement of high heat input welds and for the rationalization of construction with high-strength steels, welding efficiency has been improved by reducing or eliminating preheating and postheating in the welding stage and by adopting high heat input welding. As a result, many high-strength steels have been developed. One example is high HAZ toughness steels that achieve both high welding efficiency and high weld toughness in the fabrication of welded built-up box-shaped columns (hereafter referred to as built-up box column). Another is 550 and 590 N/mm^2 grade highly weldable steels that are produced by application of the TMCP technology.

With the 1995 Hyogo-ken Nanbu Earthquake as a turning point and along with the development of various energy absorbing devices, damage control design became spotlighted as a methodology to minimize damage to primary structural frame members even in huge earthquakes and to permit the continuous use of the essential functions even after the earthquake. Through this background, the cross-ministry collaboration project titled "Development of New Building Structural System Using Innovative Materials" was started to develop such structures that hold principal members of buildings within their elastic behavior and protect them against damage even in an earthquake of seismic intensity class 7. To meet these requirements, 780 N/mm^2 grade ultrahigh strength steels (H-SA700) with high yield ratio of 98% have been developed. According to a similar concept, 490 and 590 N/mm^2 grade steels have been developed with a high yield ratio of 90% or less.

Cold press-formed HSSs that can be welded with robots have also been developed to take the place of built-up box columns. When conventional cold press-formed HSSs BCP325 are used as columns, their corners are cold formed. With the through-diaphragm type, a safety factor is imposed by additional design requirements, such as the reduction of full plastic strength in partial collapse of frames to reduce the stress in the column-diaphragm welded connections. In contrast, the high-performance cold press-formed HSSs BCP325T has its weld quality assured by overlapping weld beads on the base metal at the column-diaphragm welded connection and further by placing reheat beads on the weld beads. This welding procedure has made it possible to handle the BCP325T columns under the same design conditions as the built-up box columns. Furthermore, the toughness and welding performance of the steel plates used for the cold press-formed HSSs have been dramatically improved. Commercialized steel pipe columns (or columns made from TMCP high-performance cold press-formed HSSs for building structures) can be fabricated under the same design conditions as BCP325T columns even when the same weld buildup method as that of BCP325 pipe columns is used. Cold press-formed HSSs with a high strength of 550 and 590 N/mm^2 grade have also been developed and used as columns of large-scale buildings.

2.2 Product lineup of high strength steel plates and high-performance cold press-formed HSSs for buildings

Nippon Steel has lined up high strength steel plates for building structures while responding to the above-mentioned diverse needs for building steel. The BT-HT series of high strength steel plates for building structures are shown in **Table 1** and the BCHT series of high-performance cold press-formed HSSs are shown in **Table 2**.

The BT-HT series has a lineup of 490 to 780 N/mm^2 grade low-yield ratio steels BT-HT325, 355, 385, 440 (= SA440), and 630-ES.

Table 1 "BT-HT" series of high strength steel plate products

Steel	Thickness (mm)	YS (N/mm^2)	TS (N/mm^2)	YR (%)	$_{v}E_{0}$ (J)
BT-HT325B, C	40<t≤100	325–445	490–610	≤80	27≤
BT-HT355B, C	40<t≤100	355–475	520–620	≤80	27≤
BT-HT385B	12≤t≤100	385–505	550–670	≤80	70≤
BT-HT385C	16≤t≤100				
BT-HT440B, C	19≤t≤100	440–540	590–740	≤80	47≤
BT-HT440B-SP, C-SP	19≤t≤100	440–540	590–740	≤80	70≤
BT-HT630B-ES, C-ES	40≤t≤100	630–750	780–930	≤85	47≤
BT-HT400C	16<t≤100	400–550	490–640	≤90	70≤
BT-HT500C	19≤t≤100	500–650	590–740	≤90	70≤
BT-HT700A, B	6≤t≤50	700–900	780–1 000	≤98	47[*1]≤
BT-HT880B, C	9≤t≤50	880–1 060	950–1 130	≤98	70[*2]≤

*1: Test temperature at −20°C, *2: 12<t≤50

Table 2 "BCHT" series of high performance cold press-formed HSSs products

Steel	Thickness (mm)	YS (N/mm^2)	TS (N/mm^2)	YR (%)	$_{v}E_{0}$ (J)	
					Flat part	Corner part
BCHT325BTF, CTF	16≤t≤40	325–445	490–610	≤80	70≤	70≤
BCHT385B, C	19≤t≤50	385–505	550–670	≤80	70≤	-
BCHT385BT, CT	19≤t≤50	385–505	550–670	≤80	70≤	70≤
BCHT385BTF, CTF	16≤t≤60	385–505	550–670	≤80	70≤	70≤
BCHT440B, C	19≤t≤50	440–540	590–740	≤80	70≤	-
BCHT400B, C	19≤t≤50	400–550	490–640	≤85	70≤	-

In the 590 N/mm² grade, the lineup includes the conventional BT-HT440 as well as the low-preheat temperature BT-HT440-SP without preheating up to a plate thickness of 100 mm by optimizing the steel composition and by applying the TMCP technology to meet the need for eliminating preheating during on-site welding. The BT-HT630-ES has its weldability improved by optimizing the chemical composition from conventional 780 N/mm² grade steels. We have also augmented our lineup of high-yield point steels BT-HT400, 500, 700 (= H-SA700), and 880 for elastic design with the yield ratio reduced as steels for columns to meet various design needs.

Electroslag welding (ESW) and multiple-electrode submerged arc welding (SAW) are generally used in the fabrication of built-up box columns frequently adopted in superhigh-rise buildings. The heat input ranges from 500 to 1 200 kJ/cm. When such high heat input welding is applied to conventional steels, the weld heat-affected zone (HAZ) microstructure coarsens to reduce the toughness and increase the brittle fracture risk.[5)] To simultaneously meet the two needs of welding with high efficiency and increasing the weld toughness, we developed the HAZ refining and toughening technology HTUFF[6)] and applied it to BT-HT325, 355, 385, 440, and 440-SP to commercialize the high HAZ toughness steels (-HF). We are now promoting our high-HAZ toughness steels for use in heavy-section members with severe welding conditions to meet these needs.

In addition to the BCP325 and the BCP325T, the lineup includes 490 N/mm² and 550 N/mm² grade TMCP cold press-formed HSSs BCHT325BTF, BCHT325CTF, BCHT385BTF, and BCHT-385BCTF. These pipes have their toughness and weld performance improved by using TMCP steel as the base metal, do not require complicated welding process management as BCP325T does, and exhibit structural performance equivalent to or better than that of BCP325T. Also, we have newly developed 590 N/mm² grade cold press-formed HSSs BCHT440B and BCHT440C and placed them on the market.

3. Thickening of 550 and 590 N/mm² Grade TMCP Steel Plates for High Heat Input Welding

3.1 Background of development

In recent years, superhigh-rise buildings have increased in seismic resistance and height and have presented a wide range of needs, such as longer spans, multiple usage, and space diversity. For this reason and from the viewpoint of improving weld quality and steel frame fabrication efficiency, building structure steel plates for built-up box columns have been required to adapt to high heat input welding, including ESW of internal diaphragm connections, and to SAW of column corner joints, and to meet better weldability and greater thickness requirements. Through this background, Nippon Steel has applied the TMCP technology and developed thicker 550 and 590 N/mm² grade high HAZ toughness steels that can lower the preheating temperature.

3.2 Overview of products

In the chemical composition design of 550 and 590 N/mm² grade steels, to ensure the base metal strength, reduce the preheating temperature, and ensure the toughness of high heat input welds even in thick steel plates, we have applied the HTUFF technology and optimized the chemical composition to reduce the Martensite-Austenite (MA) microstructure.

The chemical compositions and mechanical properties of the developed steels BT-HT385C-HF (70 mm thick) and BT-HT440C-SP-HF (100 mm thick) are shown in **Tables 3** and **4**, respectively. Both steels have low C_{eq} and P_{CM} and excellent weldability and fully satisfy the mechanical property requirements.

3.3 Performance of high heat input welds

To confirm the high heat input weld performance, which was the target of our development, two full-scale built-up box column specimens each (□−900×900×L3 000) were prepared by using the developed steels BT-HT385C-HF and BT-HT440C-SP-HF in the skin plates of the columns and were then tested to verify the welded joint performance.[7)]

Table 5 lists the welded specimens prepared. The outline and results of the ESW (inner diaphragm connection) test are described below. The test variables of the box column specimens were thickness (2 levels of 60 and 75 mm) and strength (2 levels of 490 and 550 N/mm²). Three inner diaphragms were installed in each specimen. The specimens were welded at a remarkably high heat input of 1 400 kJ/cm.

Table 3 Chemical composition

Steel	Thickness (mm)	C (%)	Si (%)	Mn (%)	P (%)	S (%)	C_{eq} (%)	P_{CM} (%)
BT-HT385C-HF	70	0.08	0.15	1.40	0.008	0.003	0.40	0.19
Specification	-	≤0.20	≤0.55	≤2.00	≤0.020	≤0.008	≤0.42*1	≤0.27*1
BT-HT440C-SP-HF	100	0.10	0.07	1.52	0.007	0.002	0.37	0.22
Specification	-	≤0.12	≤0.55	≤1.60	≤0.020	≤0.008	≤0.47*2	≤0.22

*1: 50<t≤100, *2: 40<t≤100

Table 4 Mechanical properties

Steel	Thickness (mm)	YS or YP (N/mm²)	TS (N/mm²)	YR (%)	EL (%)	$_vE_0$ (J)	RA (%)
BT-HT385C-HF	70	484	621	78	28	306	72
Specification	-	385–505	550–670	≤80	20≤*1	70≤	25≤
BT-HT440C-SP-HF	100	471	629	75	27	232	70
Specification	-	440–540	590–710	≤80	20≤*1	70≤	25≤

*1: for No.4 specimen (JIS Z 2241)

Figure 1 shows the specimen sampling positions for the Charpy impact test and the weld metal tensile test (BOND: weld fusion line, DEPO: weld metal, HAZ: base metal weld heat affected zone). The Charpy impact test results and the weld metal tensile test results are shown in **Fig. 2** and **Table 6**, respectively. The developed steels BT-HT385C-HF and BT-HT440C-SP-HF both showed an average Charpy impact absorbed energy value of 70 J even for high heat input ESW exceeding 1 000 kJ/cm and displayed good toughness performance. The tensile strength of the weld metal also satisfied the specified strength of the inner diaphragm base metal.

Based on the above results, Nippon Steel has developed and launched the BT-HT385C-HF and BT-HT440C-SP-HF heavy steel plates that meet the strength, weldability, and weld metal toughness requirements.

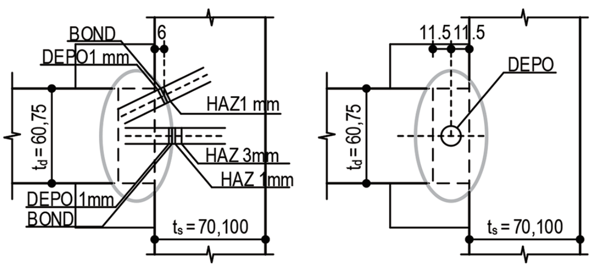
4. 590 N/mm² Grade TMCP Cold Press-Formed HSSs

4.1 Background of development

With the increasing use of welding robots in recent years, cold press-formed square steel pipe-H-shaped steel beam structures have become principal building structures in Japan. Cold press-formed square steel pipe columns (hereinafter referred to as press-formed columns) have been used in large distribution warehouses and many other large buildings. Recently, press-formed columns have been increasingly used as columns of many superhigh-rise buildings. To meet these needs, Nippon Steel Metal Products Co., Ltd. has been pushing ahead with the development of higher-strength press-formed columns and has recently developed the press-formed columns BCHT440 with a specified design strength about 35% higher than that of the conventional BCP325 columns.

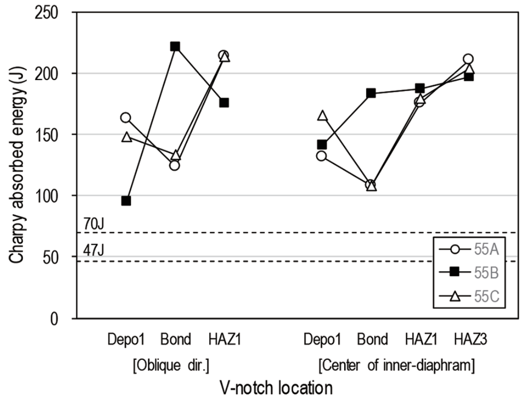
Table 5 Specimens of ESW connection

No	Column skin-plate (thickness)	Inner diaphragm (thickness)	Welding consumables (JIS Z 3353)	Heat input (kJ/cm)
55A	BT-HT385C-HF (70 mm)	BT-HT385B (75 mm)	YES602-S/ FES-Z	1 127–1 313
55B		BT-HT385B (60 mm)		982–1 082
55C		BT-HT325B (75 mm)	YES501-S/ FES-Z	1 119–1 335
59A	BT-HT440C-SP-HF (100 mm)	BT-HT385B (75 mm)	YES602-S/ FES-Z	1 268–1 353
59B		BT-HT385B (60 mm)		1 035–1 163
59C		BT-HT325B (75 mm)	YES501-S/ FES-Z	1 219–1 424

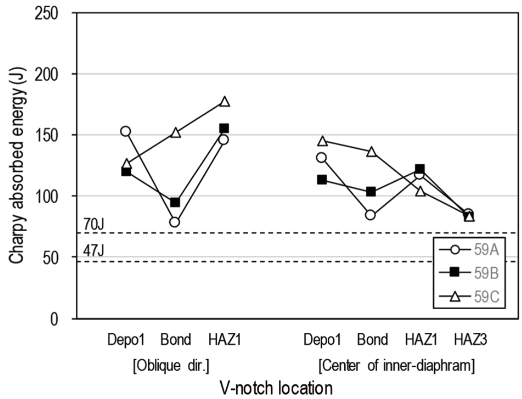


(a) Charpy impact test (b) Tensile test

Fig. 1 Specimens and their locations of Charpy impact test and tensile test for ESW connection



(a) BT-HT385C-HF



(b) BT-HT440C-SP-HF

Fig. 2 Results of Charpy impact test for ESW connection

Table 6 Results of tensile test for ESW weld metal

No	Column skin-plate (thickness)	YS or YP (N/mm^2)	TS (N/mm^2)	EL (%)	Target TS (N/mm^2)
55A	BT-HT385C-HF (70 mm)	458	643	25	550≤
55B		442	621	29	
55C		462	637	26	490≤
59A	BT-HT440C-SP-HF (100 mm)	468	647	24	550≤
59B		467	629	23	
59C		424	559	30	490≤

4.2 Overview of products

The chemical compositions of the BCHT440 steels are shown in **Table 7**. Their mechanical properties are shown in **Table 8**. The specified yield strength is 440 N/mm^2. Two grades, or grades B and C, are used to distinguish whether or not the through-thickness properties are guaranteed. For toughness, a Charpy absorbed impact energy of 70 J or more is guaranteed at 0°C for the flat area. This is the highest level for a building structural material for a flat area. The maximum plate thickness is 50 mm.

The carbon equivalent (C_{eq}) and the weld crack susceptibility composition (P_{CM}) are specified as weld properties.

4.3 Weld joint performance and structural performance as column members

The weld joint performance of BCHT440 and its structural performance as column members are described below. **Table 9** shows the chemical compositions of the specimens used to evaluate the weld performance of BCHT440. **Table 10** shows the mechanical properties of the flat and corner areas. **Table 11** shows the welding procedure records.

Figure 3 (a) shows the weld metal Charpy impact test specimen sampling position and **Table 12** shows the impact test results of the weld metal at a test temperature of 0°C. The specimen was a JIS Z 2242 V-notch specimen and was taken mainly at 6 mm inside of the outer surface.

Figure 4 shows the Vickers hardness test results of the weld metal. As shown in Fig. 3 (b), the Vickers hardness was measured at 2 mm inside of the outer surface and with a force of 98 N. The maximum hardness of the welded joint was below 350 HV.

Structural performance as a column member with a diaphragm was evaluated by the three-point bending test. The specimen was loaded in the 45° direction to evaluate the performance of fracture-

Table 7 Chemical compositions

Steel	C (%)	Si (%)	Mn (%)	P (%)	S (%)	N (%)	Thickness (mm)	C_{eq} (%)	P_{CM} (%)
BCHT440B	≤0.12	≤0.55	≤1.60	≤0.030	≤0.008	≤0.006	19≤t≤40	≤0.44	≤0.22
BCHT440C				≤0.020			40<t≤50	≤0.47	

Table 8 Mechanical properties

Steel	YP (N/mm^2)	TS (N/mm^2)	YR (%)	EL*			$_vE_0$
				Thickness (mm)	Test piece*	(%)	(Flat) (J)
BCHT440B	440≤	590≤	≤80	19≤t≤25	5	33≤	70≤
BCHT440C	≤540	≤740		25<t≤50	4	20≤	70≤

* Test piece for tensile test: JIS Z 2241

Table 9 Chemical compositions of specimens

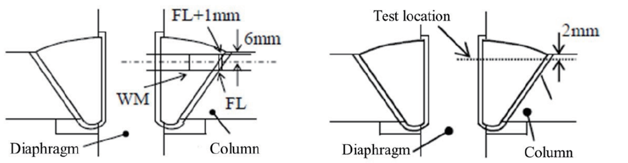
Spec. No.	Section D×t (mm)	C (%)	Si (%)	Mn (%)	P (%)	S (%)	N (%)	C_{eq} (%)	P_{CM} (%)
T50	□600×50	0.08	0.26	1.54	0.012	0.003	0.003	0.41	0.18
T32	□450×32	0.09	0.22	1.57	0.008	0.003	0.003	0.37	0.19

Table 10 Mechanical properties of specimens

Spec. No.	Flat area					Corner area			
	Test piece	YP (N/mm^2)	TS (N/mm^2)	EL (%)	YR (%)	Test piece	YP (N/mm^2)	TS (N/mm^2)	YR (%)
T50	4	482	644	31.9	75	4	707	776	91
T32	1A	455	626	23.5	73	1B	663	746	89

Table 11 Welding conditions

Spec. No.	Maximum heat input (kJ/cm)		Maximum interpass temperature (°C)		Pass
	Results	Management	Results	Management	
T50	30.4	≤30	218	≤250	30
T32	28.0		205		15



(a) Charpy impact tests (b) Hardness distribution tests

Fig. 3 Positions of specimens of Charpy impact tests and hardness distribution tests

Table 12 Charpy impact test results of welded joints

Spec. No.	Column-diaphragm joint (Corner area)	
	FL+1 mm	FL
T50	177	136
T32	184	174

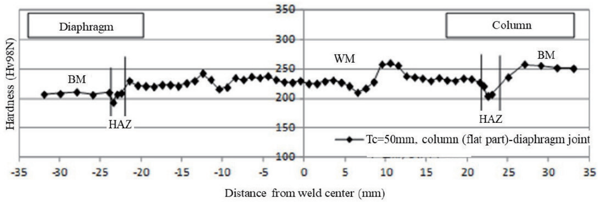


Fig. 4 Hardness distribution test results of welded joints

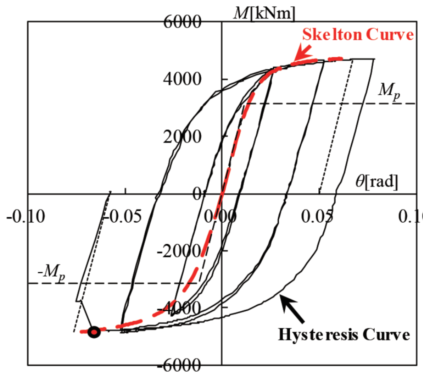


Fig. 5 Hysterisis behavior of BCHT440

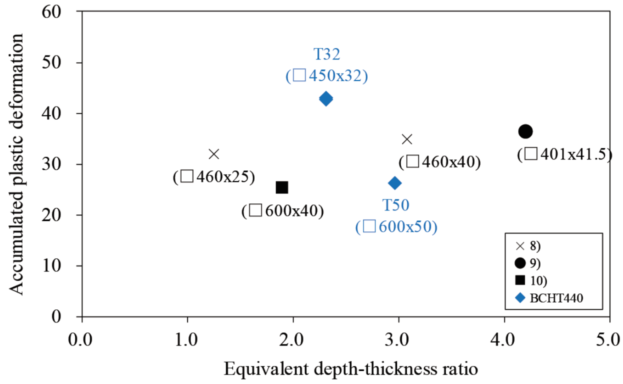


Fig. 6 Effect of depth-thickness ratio on accumulated plastic deformation

critical corner welds. As an example, **Fig. 5** shows the hysteresis behavior of BCHT440 with a thickness of 32 mm. It was confirmed that, in all specimens, a crack occurred near the weld metal and ductilely propagated toward the base metal. After the column base metal necked and plastically deformed fully, the crack penetrated through the column base metal.

Figure 6 shows the 45° direction three-point bending results of BCHT440 and other equivalents in literature.[8–10] The accumulated plastic deformation ratio is shown along the vertical axis and the equivalent width-thickness ratio $1/\alpha$ is shown along the horizontal axis. The α is calculated by:

$$\alpha = (\sigma_y/E) \cdot (D/t)^2$$

where σ_y is the yield point of the flat area of the specimen, E is Young's modulus, D is the diameter of the specimen, and t is the thickness of the specimen. The cumulative plastic deformation ratio satisfies the required column performance of 590 N/mm^2 grade cold press-formed HSSs.

The above results show that the cold press-formed HSSs BCHT440 made from TMCP steel plates with a tensile strength of 590 N/mm^2 ensures high welded joint toughness, does not suffer premature brittle fracture in the HAZ, and has excellent deformation performance.

The welded joint performance and structural performance of column members of BCHT440 are not introduced in this paper. For the details, see Reference 11).

5. Conclusions

In this paper, we have described the application of 550 and 590 N/mm^2 grade TMCP steel plates for large heat input welding to thick sections and the development of cold press-formed HSSs made from 590 N/mm^2 grade TMCP steel plates. When we apply the TMCP technology and the HAZ refining and toughening technology HTUFF to high strength steel plate for building structures, we can achieve both high strength and welding workability. We will promote the development of steels with even higher strength and better weldability, the development of new welding materials conducive to the rationalization of welding conditions, and the application of soft joints (undermatching joints).[12–14] With the development and maintenance of related technologies, we will meet the needs for streamlining the fabrication of large and heavy section steel columns.

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Hiroshi ITO
Chief Manager, Head of Section, Dr.(Eng.)
Building Products Engineering Section
Construction Products Engineering Dept.
Osaka Office
4-5-33 Kitahama, Chuo-ku, Osaka City, Osaka Pref.
541-0041

Itaru SUZUKI
Senior Manager
Building Products Engineering Section-I
Building Products Engineering Dept.
Construction Products Development Div.
Plate & Construction Products Unit

Yusuke SUZUKI
Chief Manager, Head of Section, Ph.D.
Building Products Engineering Section-I
Building Products Engineering Dept.
Construction Products Development Div.
Plate & Construction Products Unit

Masaki ARITA
Senior Researcher
Research Section-I
Steel Structures Research Dept.-II
Steel Structures Research Lab.
Steel Research Laboratories

Masato NIKAIDO
Senior Researcher
Research Section-I
Steel Structures Research Dept.-II
Steel Structures Research Lab.
Steel Research Laboratories

Tomoki URAKAWA
Senior Manager
Kimitsu Plate Quality Control Dept.
Quality Management Div.
East Nippon Works

Haruhiko NAKAGAWA
Group Manager
Building Products Development Dept.
Nippon Steel Metal Products Co., Ltd.