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Characteristics and Application of TS 520 N/mm^2 Class SHH Shapes Manufactured by Thermo-Mechanical Control Process (TMCP) for Building Frames "HBL™-H355"

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Abstract:

JFE Steel has applied its original TMCP technology to H-shaped steel, and 520 N/mm^2 class steel "HBL™-H355", which has the highest strength in Japan for fixed outer dimension H-shaped steel, has been supplied, and widely used in high-rise buildings, etc. This paper describes the characteristics of "HBL-H355" and the features of the product. Trial design was carried out in the case of replacing girder material with H-shaped steel of 490 N/mm^2 class which is the general strength to 520 N/mm^2 class, and this paper introduces the effect of weight reduction by strengthening.

1. Introduction

Since the Great East Japan Earthquake on March 11, 2011, even higher seismic resistance has been required in buildings, and accompanying the greater heights and larger spans of structures in recent years, examples of the application of steel materials with both larger sections and higher strength have also increased. Against this background, in 2011, JFE Steel developed tensile strength (TS) 520 N/mm^2 class SHH shapes "HBL™-H355," which are the highest strength fixed outer dimension H-shaped steel in Japan, while having the same yield ratio (80 % or less) and equivalent carbon content (0.44 % or less) as 490 N/mm^2 class steel (SN490) for building structures. The new steel was developed by applying JFE Steel's original TMCP (Thermo-mechanical control process) technology to shape steel, which utilizes hot rolling technology and the company's unique shape steel cooling device, "*Super*-OLAC™S". The developed steel also received Certification of the Minister of Land, Infrastructure, Transport and Tourism (MSTL-0314) in 2011. HBL-H355 has been adopted widely as an H-shaped steel with high toughness and high earthquake resistance, and contributes to economical, efficient design by reducing the weight of steel materials, which is possible by applying higher strength material in structural members.

This report presents a product overview of HBL-H355, together with a brief explanation of the performance as structural members, features of the product and handling of the design conditions in structural design. The merits of weight reduction by substituting the 520 N/mm^2 class steel for the conventional 490 N/mm^2 class steel are also described based on the results of trial design of a high-rise office building. Finally, the record of adoption up to the present is introduced.

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Table 1 Chemical compositions of HBL™-H355

(mass%)

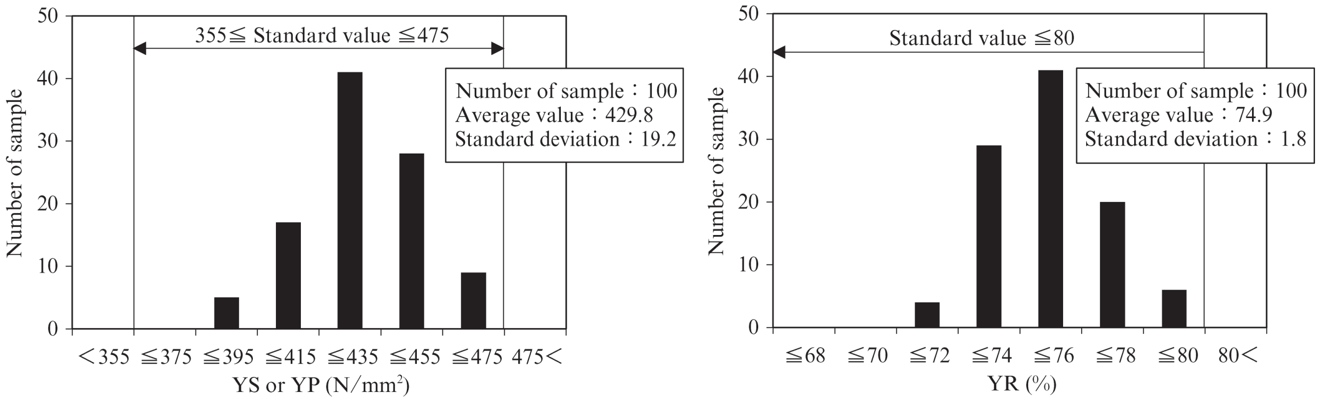
	Thickness	C	Si	Mn	P	S	C_{eq}	P_{CM}*
HBL-H355B	t≦40	≦0.20	≦0.55	≦1.65	≦0.030	≦0.015	≦0.44	≦0.29
HBL-H355C	t≦40	≦0.20	≦0.55	≦1.65	≦0.020	≦0.008	≦0.44	≦0.29

C_{eq} = C + Si/24 + Mn/6 + 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
* By agreement between the parties, it is possible to apply P_{CM} instead of C_{eq}.

Table 2 Mechanical properties of HBL™-H355

<table>
<tr><th></th><th>Thickness</th><th>YP orYS
(N/mm^2)</th><th>TS
(N/mm^2)</th><th>YR
(%)</th><th>EL
(%)</th><th>$_vE_{0°C}$
(J)</th><th>RA_Z
(%)</th></tr>
<tr><td>HBL-H355B</td><td>t≦40</td><td rowspan="2">355 ～ 475</td><td rowspan="2">520 ～ 640</td><td rowspan="2">≦80</td><td rowspan="2">≧19</td><td rowspan="2">≧27</td><td>—</td></tr>
<tr><td>HBL-H355C</td><td>t≦40</td><td>≧25 (Ave.)
≧15 (each)</td></tr>
</table>

YP: Yield point YS: Yield strength TS: Tensile strength YR: Yield ratio EL: Elongation
$_vE_{0°C}$: Charpy absorbed energy at 0°C RA_Z: Reduction of area in Z-direction



(a) Yield point or Yield strength (b) Yield ratio

Fig. 1 Statistical data

2. Properties of Steel

2.1 Standards of Steel

Table 1 and **Table 2** show the standard values of the chemical composition and mechanical properties of HBL-H355, respectively. A low yield ratio of 80 % or less, design strength of 355 N/mm^2 and a narrow YP range are obtained, while securing weldability equivalent to that of SN materials, by adopting a chemical composition conforming to the SN standards (JIS G 3136, Japanese Industrial Standards) and making full use of TMCP technology utilizing JFE Steel’s original shape steel cooling equipment, “*Super*-OLACS.”

2.2 Production Record

Figure 1 shows the statistical data for the results of production for yield strength and the yield ratio. The average values and standard deviation of the data are also shown. The results for both data are generally close to a normal distribution, and the average value of yield strength is clearly larger than the lower limit of the standard value, while the average value of the yield ratio is also sufficiently smaller than the upper limit of the standard.

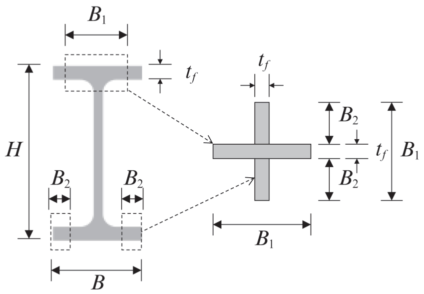
3. Member Experiments

3.1 Outline of Experiments

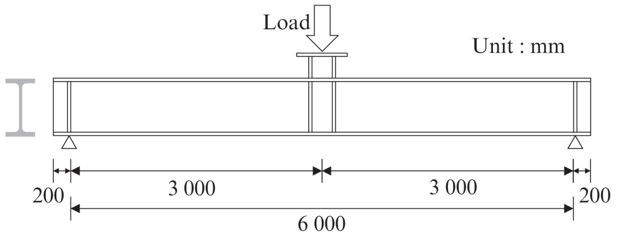
A stub column test and a bending test were conducted to verify the buckling performance as members. A list of the test specimens is given in **Table 3**, and the shape of the test specimens is shown in **Fig. 2**. The shape of the stub column test specimen is a cruciform section prepared by welding assembled flat plates cut from the upper and lower flanges of H-shaped steel. The height of the test specimen is 3 times the width B_1. The results of a tensile test of the material used in the member test are shown in **Table 4**.

Table 3 List of test specimens

Test	No.	Cross section	Rank[1]	
			Flange	Web
Compression	1	B_1 = 280 mm, tf = 32	FA	
	2	B_1 = 230 mm, tf = 40	FA	
Bending	3	H-800×400×19×32	FA	FA
	4	H-800×350×19×40	FA	FA



(a) Compression test



(b) Bending test

Fig. 2 Shape of test specimens

Table 4 Results of tensile test

	Yield stress (N/mm²)	Tensile stress (N/mm²)	Yield ratio (%)	EL (%)
Flange tf = 32.0	406	556	73.0	28
Flange tf = 40.0	395	540	73.1	31

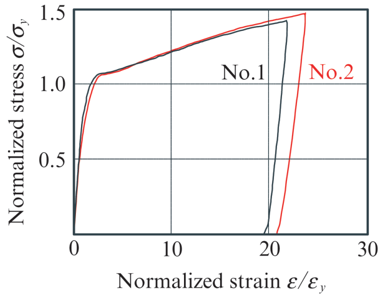


Fig. 3 Stress - strain relationship (Compression test)

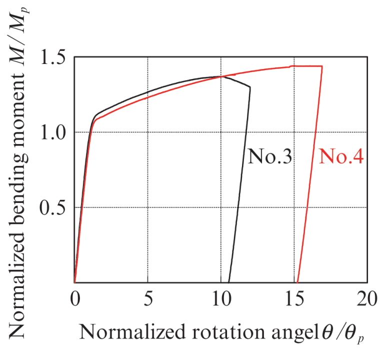


Fig. 4 Normalized bending moment - rotation angle relationship (Bending test)

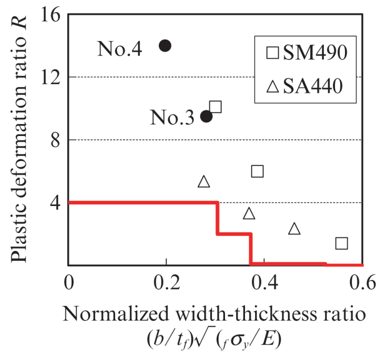


Fig. 5 Normalized width-thickness ratio - plastic deformation ratio relationship (Bending test)

3.2 Results of Stub Column Test

The stress-strain relationship is shown in **Fig. 3**. Obtained stress and strain have been normalized by the calculated yield stress σ_y and yield strain ε_y, respectively. Here, the test was discontinued before completion (before the specimens failed) because no decrease in durability was observed in any of the specimens after reaching the loading limit (10 MN). However, because the ductility factor ($\mu=\varepsilon_{max}/\varepsilon_y$) at the time of the maximum deformation exceeded the ductility factor $\mu\geq5$ (plastic deformation ratio $R\geq4$) required for the FA rank in Recommendation for Limit State Design of Steel Structures[1], it can be said that the steel has a sufficient plastic deformation capacity.

3.3 Results of Bending Test

The normalized bending moment-rotation angle relationship is shown in **Fig. 4**. Obtained plastic moment and rotation angle have been normalized by the calculated plastic moment M_p and the rotation angle when the moment becomes plastic moment θ_p, respectively. The maximum bending moment reached approximately 1.4 times full plastic strength. Although durability decreased in specimen No. 3 accompanying the occurrence of local buckling, no rapid decrease in durability was observed in specimen No. 4, and loading was stopped on reaching about 1/10 rad due to the limitation of the loading device. **Figure 5** shows the rela-

Table 5 HBL-H355 section table

Depth \ Width		300						350			400		
		22	25	28	32	36	40	32	36	40	32	36	40
600	9												
	12	●	●										
	14	●	●	●									
	16	●	●	●									
650	9												
	12	●											
	14	●	●										
	16	●	●	●									
700	9												
	12	●	●										
	14	●	●	●									
	16	●	●	●	●			●					
750	12												
	14	●	●					●					
	16	●	●	●				●	●				
800	14	●	●	●									
	16	●	●	●	●			●	●		●	●	
	19							●	●	●	●	●	●
850	14												
	16							●			●		
	19							●	●		●	●	
900	14												
	16							●			●		
	19							●	●	●	●	●	●
950	16							●			●		
	19				●	●		●	●		●	●	
1 000	16							●			●		
	19				●	●		●	●	●	●	●	●

tionship between the normalized width-thickness ratio of the flange and the plastic deformation ratio *R*. This figure also shows the demands of the plastic deformation ratio based on the literature[1)] and the results of tests of other steel grades in the past literature[2)]. Since the results of the test conducted here greatly exceed the demands of the plastic deformation ratio, it can be understood that HBL-H355 possesses the same plastic deformation capacity when compared with other steel grades.

4. Features of HBL™-H355

4.1 Product Sizes

Table 5 shows a list of the available product sizes. HBL-H355 covers the full large section range of JFE Steel's line of fixed outer dimension H-shaped steel, "Super HISLEND-H," and has been covered including a total of 81 sizes in 19 series with depths from 600 mm to 1 000 mm and widths from 300 mm to 400 mm. This size range consists mainly of sections in which the width-thickness ratio classification of beams is FA, and forms a repertoire of sections that enables easy use in designs. Dimensional accuracy is also equal to that of the conventional steels of the "Super HISLEND-H" line.

Table 6 Welding material

	Type	Use
SMAW	JIS Z 3211 E4916	Assembling welding
	JIS Z 3211 E6216-N1M1U	Assembling welding Regular welding Repair welding
GMAW	JIS Z 3312 YGW11	Assembling welding
	JIS Z 3312 YGW18	Assembling welding Regular welding Repair welding
	JIS Z 3313 T550T1-1CA-U	
	JIS Z 3313 T550T1-0CA-U	

Table 7 Preheating condition

Welding process	Plate thickness (mm)		
	t<25	25≦t<32	32≦t≦40
SMAW	unnecessary	unnecessary	50°C
GMAW	unnecessary	unnecessary	unnecessary

Table 8 Welding condition

Position	Welding process	Welding heat input (kJ/cm)	Interpass temperature (°C)
Downward Horizontal	GMAW	≦30	≦250

4.2 Welding Procedure

The welding procedure conforms to the Japanese Architectural Standard Specification JASS6 Steel Work (2018)[3)], and the welding procedure and quality control are the same as those for JIS standard 520 N/mm^2 class steel plates used as building materials. **Table 6** shows the welding materials that do not require weld testing. As representative welding procedures, **Table 7** and **Table 8** show the preheating conditions and the welding conditions, respectively. It should be noted that the preheating and welding conditions can be set separately in cases where a validation test has been conducted and safety has been confirmed. The y-groove weld cracking test in accordance with JIS Z 3158 and welded joint test have been conducted under the conditions in Tables 7 and 8, and the fact that this steel possesses satisfactory weldability has been reported in previous reports[4, 5)].

4.3 Discussion of Design Conditions

4.3.1 Discussion of interval of lateral buckling stiffener of beams

In order to control lateral buckling and secure the required deformation capacity in beams, various guidelines, regulations and standards[1, 7, 8], beginning with the Commentary on Structural Regulation of the Building Standard Law of Japan (2020)[6], specify the interval at which lateral buckling stiffeners are to be installed. The interval of lateral buckling stiffener is set according to one of the two design equations shown below, and the coefficients A, B and C are determined corresponding to the strength of the steel.

i) Method of providing lateral bracing at equal intervals along the full length of the beam

$$\lambda_y \leqq A + 20n$$

λ_y: slenderness ratio about weak axis of beam (mm)
n: number of lateral bracing members
A: for 400 N/mm^2 class steel, 170; for 490 N/mm^2 class steel, 130

ii) Method of providing lateral bracing mainly in parts near the ends of the beam

$$l_b \cdot h / A_f \leqq B \quad \text{and} \quad l_b / i_y \leqq C$$

l_b: interval of lateral buckling stiffener (mm)
h: depth of beam (mm)
A_f: cross-sectional area of compressive flange (mm^2)
i_y: radius of gyration of area about weak axis of beam (mm)
B: for 400 N/mm^2 class steel, 250; for 490 N/mm^2 class steel, 200
C: for 400 N/mm^2 class steel, 65; for 490 N/mm^2 class steel, 50

The coefficients used in these equations can be set corresponding to the strength ratio by the same concept as in the literature[6], provided there is no difference in the plastic deformation capacity due to the steel grade. According to the literature[9], it has been shown that the relationship between the general slenderness ratio and the plastic deformation ratio has almost the same value independent of the steel grade, and within the range of the experiment in Chapter 3, it has also been confirmed that there are no large differences between HBL-H355 and other steel grades. The design equation for the interval of lateral buckling stiffener can be specified based on these facts.

4.3.2 Discussion of safety factor α

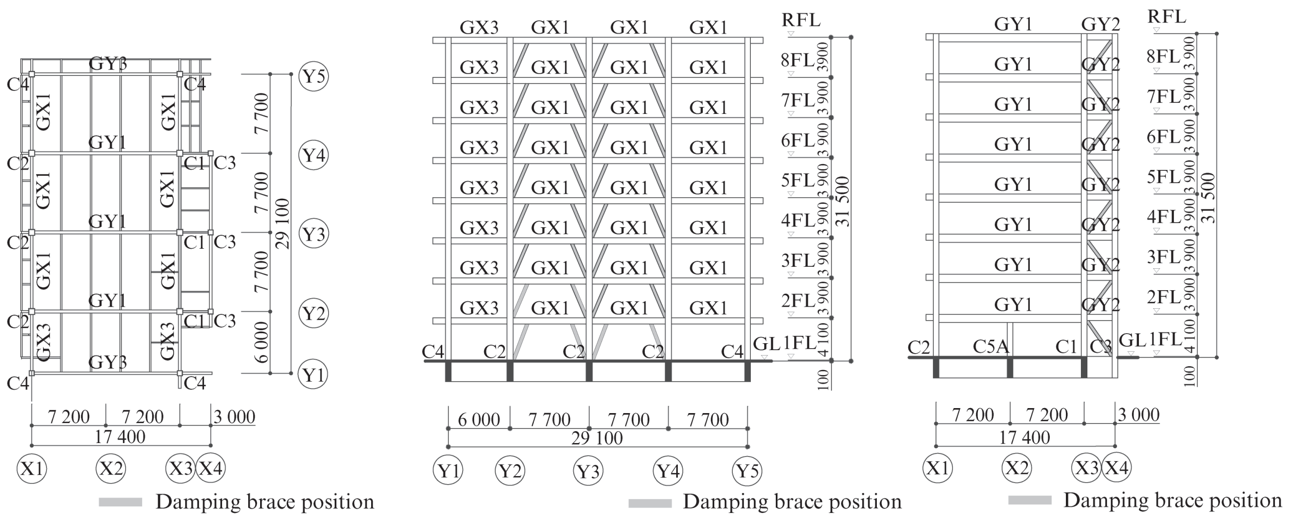
According to the literature[6], the safety factor α for the beam-column joint connections and joints is set considering stress concentration in the connection and joint part, variations in the yield point of the steel materials and the effect of the strain hardening, the plasticity of the member and the uncertainty of prediction of the collapse mechanism.

Regarding the variation of material strength, in the literature[1], the average values of the yield point and tensile strength are defined as the median values of the standard, and the degree of variation of material strength is estimated from the ratio obtained from the assumed value of the yield ratio and the yield ratio obtained from the nominal values of yield strength and tensile strength, based on the assumed value of the yield ratio obtained on the assumption that its specified range is 3σ above and below those average values. As the variation of the material strength of HBL-H355, according to **Fig. 1**(b), which showed the statistical data for the yield ratio, the average value of the yield ratio is 0.749, the standard deviation is 0.018 and the assumed value of the yield ratio is 0.767. Since the yield ratio obtained from the nominal values of the yield strength and tensile strength of HBL-H355 is 0.68, the ratio of these respective yield ratios is 1.13. On the other hand, the average value of the yield ratio of H-shaped steel of SN490 material given in the literature[10] is 0.739, the standard deviation is 0.027 and the assumed value of the yield ratio is 0.766. Because the yield ratio obtained from the nominal values of the yield strength and tensile strength of the SN490 material is 0.66, the ratio of these yield ratios is 1.16. Therefore, the degree of variation of the yield ratio of HBL-H355 is considered to be equal or superior to that of H-shaped steel of the SN490 material.

In studying the rate of increase in the bending moment, from Fig. 4, which showed the normalized bending moment-rotation angle relationship under monotonic loading in the three point bending test, in the range of θ/θ_p from 2 to 8, M/M_p results in 1.13 to 1.34. The safety factor α of beam-column joint connections and joints can be set based on this value.

4.3.3 Discussion of width-thickness ratio rank

The design strength of HBL-H355 is 355 N/mm^2, which is within the applicable range (205 N/mm^2 $\leq F \leq$ 375 N/mm^2) of the width-thickness ratio specification in the Notifications in the Building Standard Law of Japan. Furthermore, from the results of the bending test in Chapter 3, the relationship of the width-thickness ratio of the flange and web and the plastic deformation ratio was also found to be equivalent to that of



(a) Framing plan (b) X3 line framing elevation (c) Y2-Y4 line framing elevation

Fig. 6 Building for trial design

Table 9 Section list

Girder	Floor	Position	Before	After	Weight reduction
GY1	7, 8, R	Full length	H-800×300×16×25	H-800×300×16×22	▲6%
	6	Full length	H-800×300×16×28	H-800×300×16×25	▲6%
	5	Full length	H-800×350×16×25	H-800×350×16×22	▲8%
	3,4	Full length	H-800×350×16×28	H-800×350×16×25	▲6%
	2	Full length	H-600×250×12×22	H-600×200×12×22	▲12%
GY3	8, R	Full length	H-800×250×16×22	same as on the left	—
	6,7	Full length	H-800×250×16×25	H-800×250×16×22	▲6%
	3,4,5	Full length	H-800×300×16×25	H-800×300×16×22	▲6%
	2	Full length	H-600×250×12×22	H-600×200×12×22	▲12%

other steel grades. Based on these facts, in calculations of the width-thickness rank of HBL-H355, the rank can be specified according to the equation shown in the Notifications in the Building Standard Law of Japan.

5. Comparison with Steel Weight of 490 N/mm² Class Steel by Trial Design

5.1 Study Conditions

Trial design was carried out for cases in which 490 N/mm² class steel and 520 N/mm² class steel were used in the steel beams. **Figure 6** shows the framing plan and frame elevation of the typical floor of the building used in the trial design. Assuming an 8-story high-rise office building[11], the column sections are □-500 × 500 to □-600 × 600 (BCP325), and the beam sections are H-800 × 250 to 350 for GY1 and GY3 beams and H-600 × 200 to 300 for other beams. For column-beam members, members in which the width-thickness ratio is FA rank were selected so that an adequate plastic deformation capacity could be secured. The beam-column joints were a type using through diaphragms. As the structure, a rigid frame with bidirectional damping brace was used, and for the damping braces, buckling-restrained braces using the low yield point steel LY225 were selected.

In this study, first, the design was carried out using only on the 490 N/mm² class steel, after which the design was performed by replacing it with 520 N/mm² steel with the same durability as the 490 N/mm² class steel. The design was performed in accordance with Notification Route 3, and members that secured stiffness which limited the story drift angle to approximately 1/200 were selected. The story stiffness ratio satisfied 0.6 or higher for all stories, and eccentricity satisfied 0.15 or less.

5.2 Study Results

Table 9 shows an example of the beam sections before and after the substitution of the HBL-H355 steel grade, together with the weight reduction effect.

Photo 1　Osaka Umeda Twin Towers South

Photo 2　Logicross Kasukabe

Because all beams, except the short span GY2 beam, satisfied the design target of design strength and story drift angle, replacement was possible for all sections. The weight reduction effect of the members was 6 to 12 %, and the results confirmed that a weight reduction effect comparable to the strength ratio of the 490 N/mm^2 class and 520 N/mm^2 class could be obtained.

6. Application Examples

Photo 1 shows Osaka Umeda Twin Towers South. The Phase I Building was completed in 2018 with 13 floors aboveground, 3 sublevels and a maximum height of about 75 m. HBL-H355 was also adopted for the Phase II Building, which is a skyscraper scheduled for completion in 2022, and will have 38 floors aboveground, 3 sublevels and a maximum height of approximately 190 m. **Photo 2** shows Logicross Kasukabe, which was completed in 2021 with a structure with 4 floors aboveground and a total floor space of 38 000 m^2. JFE Steel's method for lateral buckling restrained steel beam[12)] was also applied to this structure, contributing to a reduction of the weight of steel materials. HBL-H355 has also been adopted widely in other structures, particularly in skyscrapers, commercial facilities and large-scale warehouses.

7. Conclusion

The product outline, structural performance of members and product features of the tensile strength 520 N/mm^2 class H-shaped steel "HBL™-H355" were explained briefly, and the merit of reduction of the weight of steel materials was shown based on a comparison in which the conventional 490 N/mm^2 class steel was replaced with HBL-H355. In the future, we will continue to develop products and technologies which are suited to the needs of customers and can contribute to society.

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