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High Performance 550 MPa Class High Strength Steel Plates for Buildings —Steel Plates with New Specified Design Strength, "HBL385," which Minimize Construction Costs in Frame Fabrication and Alleviate Environmental Burden—†

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Abstract:

JFE Steel has developed a high strength steel plate, "HBL385", with lower limit yield strength of 385 MPa, providing a combination of economic efficiency, earthquake resistance, and weldability. This developed steel has the middle strength between HBL355 and SA440, and good weldability equivalent to HBL355. Production of this steel plate was made possible for the first time by applying thermo-mechanical control process (TMCP) technology using the most advanced JFE Steel's on-line accelerated cooling system. Heat affected zone (HAZ) toughness of HBL385-E for high heat input welding was improved by applying JFE Steel's microstructural control technology for high heat input welding, "JFE EWEL," accomplishing the Charpy absorbed energy value above 70 J (average) at 0°C. The developed steel has been approved by Minister of Land, Infrastructure and Transport, and the actual application results of the developed steels are under increase.

1. Introduction

In construction, high strength materials are required for use in high-rise buildings in cities. On the other hand, in view of fracture damage in welds of column to beam joint in Hanshin-Awaji Earthquake (1995), there has been an increasing need for high performance steel products with a low yield ratio (yield point/tensile strength), high toughness, and good weldability in building frames. Moreover, reflecting recent economic conditions, reduction of construction costs are also strongly required.

In response to these needs, JFE Steel developed a 550 MPa class (lower limit yield strength: 385 MPa) steel plate, "HBL385," with the middle strength between 520 MPa and 590 MPa class steel as a steel product which possesses a combination of economy efficiency, earthquake resistance, and weldability and offers the highest economy per unit of strength[1)]. This new product was approved by Minister of Land, Infrastructure and Transport under Article 37 of the Building Standard Low of Japan in April 2002. Manufacture of this steel was made possible for the first time by applying an advanced on-line accelerated cooling device, represented by the *Super*-OLAC[2)], which is among JFE Steel's proudest technical accomplishments, and thermo-mechanical control process (TMCP) technology. To meet recent heightened requirements for toughness, a chemical

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composition which also considers HAZ toughness was adopted in this steel. JFE Steel's microstructure control technology for high heat input welding, "JFE EWEL,"[3] makes it possible to secure high toughness not only in gas-shield metal arc welding (GMAW)[4] in welds of column to beam joint, but also in parts where high efficiency high heat input welding is used[5], such as one-pass submerged arc welding (SAW, maximum heat input: approximately 70 kJ/mm), which is applied in the corner welds of welded box columns, and electro slag welding (ESW, maximum heat input: approximately 100 kJ/mm), which is used in box column diaphragm welds. A new plate, "HBL385-E," which is capable of meeting a strict toughness requirement of Charpy absorbed energy above 70 J (average) at 0°C for high heat input welding was also developed and commercialized based on the JFE EWEL technology.

This paper describes the development concept and features of HBL385 series and the performance of HBL385 plates and welded joints.

2. Development Concept of New Specified Design Strength Steel Plate, "HBL385"

As shown in **Fig. 1**, the strength levels of steel products for architectural construction which are now in use (materials which conform to JIS (Japanese Industrial Standards) and materials approved by Japan's Minister of Land, Infrastructure and Transport) are 400, 490, 520, and 590 MPa class steels (corresponding to yield point strength ranks of 235, 325, 355, and 440 MPa). In general, the use of high strength steel products increases with the height of high-rise buildings, with the aims of reducing the weight of steel materials and welding consumables by reducing the cross-section of the required building components, which is possible by using high strength materials, and reducing the burden of steel frame fabrication, transportation, and erection work. Although 590 MPa class steel (material approved by Minister of Land, Infrastructure and Transport: SA440)

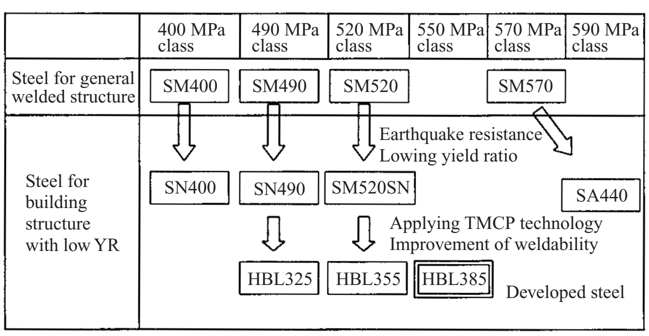


Fig. 1 Placement of HBL385 in the steel plates for buildings

is a high strength product with excellent performance, higher material costs and longer lead times cannot be avoided with this material because addition of alloy elements and a complex heat treatment process after rolling are indispensable for obtaining the required properties. Moreover, strict controls in welding are also necessary during fabrication of the steel frame, including preheating control and heat input limits. Thus, while this product has numerous advantages, for example, making it possible to reduce the thickness of extra-heavy plates and meet the requirements of parts which are subject to high axial force, its economic efficiency (cost per unit of strength) is inferior, and there are limits on parts where it can be applied.

Therefore, in response to the need for rationalization of construction costs, JFE Steel developed a 550 MPa class steel (HBL385: lower limit yield strength, 385 MPa) with an middle strength between 520 MPa and 590 MPa class steels as a steel which offers satisfactory weldability and excellent earthquake resistance in combination with excellent economic efficiency.

The chemical compositions and mechanical properties of HBL385 products are shown in **Table 1** and **Table 2**, respectively. The thickness range of HBL385 is from 19 mm to 100 mm. Although its yield point and tensile strength have been increased by 30 MPa in comparison with HBL355, the new steel has the same carbon equivalent (C_{eq}) and weld cracking parameter (P_{CM}) as HBL355, as shown in **Fig. 2** and Table 2. Therefore, the weldability of HBL385 is equal to that of the conventional steel, HBL355, and it is possible to hold welding costs in steel frame fabrication to a low level relative to the high strength of the material.

Accordingly, in comparison with the conventional steel, the weight of the steel frame used can be reduced by applying higher strength material, frame fabrication/welding labor are both reduced accompanying the reduction in frame weight, and controls of welding can be relaxed and welding time shortened in fabrication as a result of improved weldability, thereby minimizing the fabrication cost of the steel frame. **Figure 3** shows the trial calculation results of the fabrication cost for one example.

Where toughness values for steel plates are concerned, the new plate provides a Charpy absorbed energy value of more than 70 J (average) at 0°C, corresponding to the most recent high toughness requirements. As welded joint toughness, it is also possible to secure an energy value of more than 70 J (average), not only in welds of column to beam joint (GMAW), but also in the heat affected zone (HAZ) for high heat input welding such as one-pass SAW, which is used in the corner joints of box columns, and ESW in box column diaphragm welds, securing sufficient earthquake safety of structure,

Table 1 Chemical compositions of HBL385

(mass%)

Grade	C	Si	Mn	P	S	C_{eq}		P_{CM}
HBL325B	≦ 0.20	≦ 0.55	≦ 1.60	≦ 0.030	≦ 0.015	t ≦ 50	≦ 0.38	≦ 0.24
HBL325C				≦ 0.020	≦ 0.008	t > 50	≦ 0.40	≦ 0.26
HBL355B	≦ 0.20	≦ 0.55	≦ 1.60	≦ 0.030	≦ 0.015	t ≦ 50	≦ 0.40	≦ 0.26
HBL355C				≦ 0.020	≦ 0.008	t > 50	≦ 0.42	≦ 0.27
HBL385B	≦ 0.18	≦ 0.55	≦ 1.60	≦ 0.030	≦ 0.015	t ≦ 50	≦ 0.40	≦ 0.26
HBL385C				≦ 0.020	≦ 0.008	t > 50	≦ 0.42	≦ 0.27
SA440B	≦ 0.18	≦ 0.55	≦ 1.60	≦ 0.030	≦ 0.015	t ≦ 40	≦ 0.44	≦ 0.28
SA440C				≦ 0.020	≦ 0.008	t > 40	≦ 0.47	≦ 0.30

C_{eq} = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14, t : Thickness (mm),
P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

Table 2 Mechanical properties of HBL385

Grade	Thickness, t (mm)	YP (MPa)	TS (MPa)	El (%)		YR (%)	$_{V}E_{0°C}$ (J)	RA$_Z$ (%)	
HBL325B, C	40 < t ≦ 100	325–445	490–610	t ≦ 50	≧ 19*	≦ 80	≧ 27	C	≧ 25 (average)
				t > 40	≧ 21**				≧ 15 (each)
HBL355B, C	40 < t ≦ 100	355–475	520–640	t ≦ 50	≧ 19*	≦ 80	≧ 27	C	≧ 25 (average)
				t > 40	≧ 21**				≧ 15 (each)
HBL385B, C	19 ≦ t ≦ 100	385–505	550–670	t ≦ 50	≧ 26***	≦ 80	≧ 70	C	≧ 25 (average)
				t > 40	≧ 20**				≧ 15 (each)
SA440B, C	19 ≦ t ≦ 100	440–540	590–740	t ≦ 50	≧ 26***	≦ 80	≧ 47	C	≧ 25 (average)
				t > 40	≧ 20**				≧ 15 (each)

* T.P. : JIS No. 1A, ** T.P. : JIS No. 4, *** T.P. : JIS No. 5
RA$_Z$: Reduction of area in through thickness tensile test (Z)

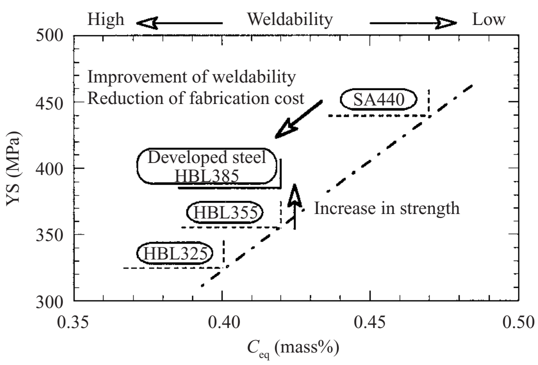


Fig. 2 Concept of the developed HBL385

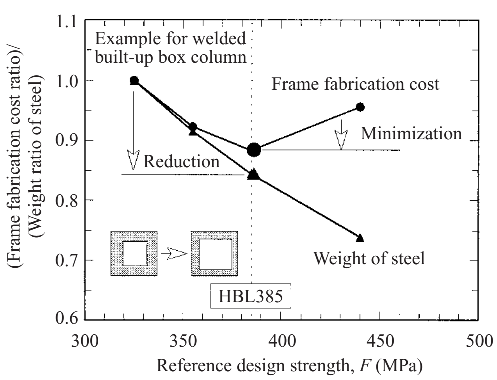


Fig. 3 Minimization of fabrication costs by using HBL385

including welded joints[6,7].

3. Alloy Design and Production Technology of Developed Steel

3.1 TMCP Technology for Low Yield Ratio High Strength Steel

JFE Steel has a long record as a pioneer in the field of TMCP and was the first steel maker in the world to apply an on-line accelerated cooling device in practical plate production. At present, all three of the company's plate mills are equipped with the advanced *Super*-OLAC, which was developed by JFE Steel and features a high cooling capacity and excellent cooling uniformity and controllability.

In comparison with the conventional HBL355, achieving high strength while avoiding increased addition of alloy elements was a technical problem in HBL385. This problem was overcome and high performance was achieved by employing an advanced accelerated cooling device, *Super*-OLAC with a high cooling rate, and controlling the rolling and accelerated cooling conditions with high accuracy. With these technologies, it is possible to produce plates with a maximum thickness of 100 mm.

Figure 4 shows the relationship between tensile strength and the cooling rate with a chemical composi-

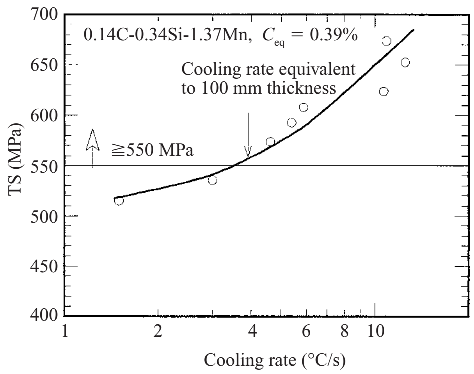


Fig. 4 Tensile strength obtained by advanced TMCP process

tion having the same C_{eq} as HBL355. With the same chemical composition as HBL355, tensile strength of 550 MPa can be secured up to a plate thickness of 100 mm. Optimization of the microstructure by high-accuracy control of the TMCP technology made it possible to develop this steel plate, which features a low yield ratio below 80% in combination with high strength above 550 MPa as well as excellent toughness, with an absorbed energy value of more than 70 J (average) at 0°C.

3.2 Improvement Technology in HAZ Toughess

In HBL385, a C_{eq} level equal to that of HBL355 is achieved by applying an accelerated cooling device with a high cooling rate. It is also possible to meet the requirement for the HAZ toughness estimation parameter for MAG welding, $f_{HAZ} \leqq 0.58\%$[8], which secures the Charpy absorbed energy above 70 J (average) at 0°C in multi-layered build-up welding.

An average energy value of more than 70 J at 0°C as the HAZ toughness for high heat input welding, such as corner welds (SAW) and diaphragm welds (ESW), can also be secured by applying JFE Steel's microstructural control technology for high heat input welding, "JFE EWEL." The JFE EWEL technology has the following features.

(1) Optimization of the alloy design, including reduction of C_{eq}, by TMCP technology using JFE Steel's advanced *Super*-OLAC with high cooling rate
(2) Minimization of the coarse grain HAZ (CG-HAZ) by using TiN
(3) Control of the intragranular microstructure of the HAZ in order to promote ferrite formation, suppress brittle phases, etc.

This technology is applicable not only to steel plates for building frames, but also to a wide range of other fields, such as plates for shipbuilding. Application of this technology makes it possible to consistently secure HAZ toughness of more than 70 J (average) at 0°C in high heat input welding such as one-pass SAW and ESW.

Figure 5 shows the relationship between C_{eq} and the 0°C Charpy absorbed energy at the fusion line (FL) in ESW (welding heat input: 80–90 kJ/mm). With steel containing approximately 0.01% Nb added, which is an effective alloy element for achieving high strength in the base material, it is not possible to satisfy the target value of 70 J with a C_{eq} values higher than 0.36%. However, an increase in toughness can be seen when Nb is not added. Moreover, in steels using the JFE EWEL technology for high heat input welding, in which fine precipitates/inclusions such as nitrides, oxides, and sulfides are controlled[9], further improvement in toughness is observed, and it is possible to secure a high Charpy absorbed energy of more than 70 J (average) at 0°C.

Photo 1 shows the microstructure of the CG-HAZ around the FL in ESW with a Nb-added steel and steel using JFE EWEL. In the Nb-added steel not applying JFE EWEL, the coarse-grained region is wide and the interior of grains where growth of grain-boundary ferrite can be seen shows a microstructure consisting mainly of upper bainite (UB). In contrast to this, in the steel in which the JFE EWEL technology was applied, the width of the CG-HAZ is reduced and the amount of ferrite is large, while formation of UB, which is a brittle phase, is reduced, resulting in a large improvement in the micro-

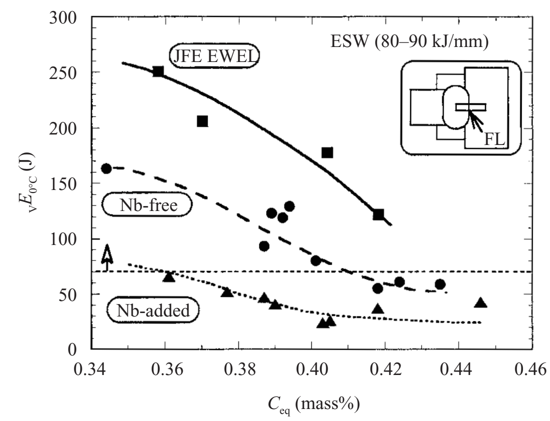


Fig. 5 Improvement of HAZ (FL) toughness for high heat input welding by suppression of C_{eq} and applying JFE EWEL technology

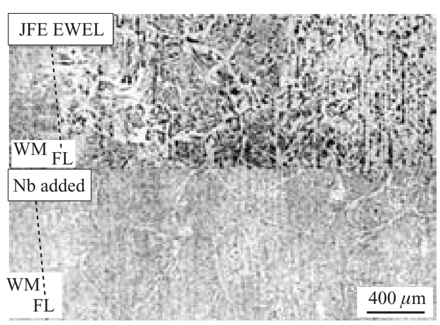


Photo 1 Microstructures at fusion line of an ESW joint of steel with applying JFE EWEL technology and Nb added steel (C_{eq} ≒ 0.40 mass%)

structure. Improvement in the intragranular microstructure is attributed to control of fine oxides and sulfides, in addition to the reduction in C_{eq} and the fact that Nb was not added.

4. Features of Developed Steel

4.1 Features of HBL385 Steel Plates

The typical chemical compositions and mechanical properties of HBL385 steel plates are shown in **Table 3** and **Table 4**, respectively. The target performance is satisfied at all plate thicknesses from 19 mm to the maximum thickness of 100 mm. In particular, Charpy absorbed energy at 0°C shows a high value of more than 200 J, indicating excellent toughness.

Where the weldability of HBL385 is concerned, **Fig. 6** shows the results of a maximum hardness test (conforms to JIS Z 3101, effect of bead length). When the bead length is more than 40 mm, maximum hardness decreases below 350HV. Moreover, in the y-groove weld cracking test, the preheat temperatures to avoid cold cracking in shielded metal arc welding (SMAW) and CO_2 gas shield metal arc welding were 50°C and room temperature (25°C or less), respectively, showing that HBL385 possesses excellent weldability equal to that of the conventional steel, HBL355.

Table 3 Chemical compositions of HBL385C

(mass%)

Thickness, t (mm)	C	Si	Mn	P	S	C_{eq}	P_{CM}	f_{HAZ}
19	0.14	0.34	1.37	0.014	0.002	0.39	0.22	0.43
35	0.14	0.21	1.26	0.013	0.002	0.37	0.21	0.41
70	0.14	0.34	1.37	0.014	0.002	0.39	0.22	0.43
100	0.14	0.34	1.37	0.014	0.002	0.39	0.22	0.43

$f_{HAZ} = C + Mn/8 + 6(P + S) + 12N - 4Ti$ (if Ti $\leqq$ 0.005%, then Ti = 0) ; Index to the HAZ toughness

Table 4 Mechanical properties of HBL385C

Thickness, t (mm)	YS (MPa)	TS (MPa)	El (%)	YR (%)	$_{V}E_{0°C}$ (J)	RA_Z (%)
19	422	552	44	76	289	74, 70, 74
35	458	593	32	77	269	73, 73, 72
70	445	596	31	75	290	76, 74, 74
100	432	578	31	75	247	72, 69, 71

Tensile test : Full thickness (JIS No. 5)-C (19t), 1/4t (JIS No. 4)-C (35, 70, 100t)
Charpy test : 1/4t-C, RA_Z : Z

4.2 Welded Joint Performance of HBL385

As examples of the welded joint performance of HBL385 steel plates, **Table 5** shows the mechanical properties of welded joints in CO_2 welding, and **Table 6** shows the results of a cross-shaped welded joint test of the "diaphragm"-"column" and "skin plate"-"beam flange." In the CO_2 welded joint, tensile strength amply satisfying the specification of base material was obtained, and a high energy value of more than 70 J (average) at 0°C was observed at all notch positions. In the cross-shaped welded joint, the fracture position was the diaphragm or base material part of the beam flange.

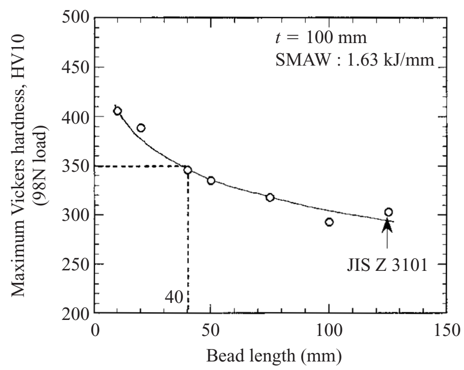


Fig. 6 Maximum hardness test result of HBL385C

Table 5 Mechanical properties of HBL385C's CO_2 welded joint

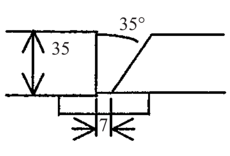
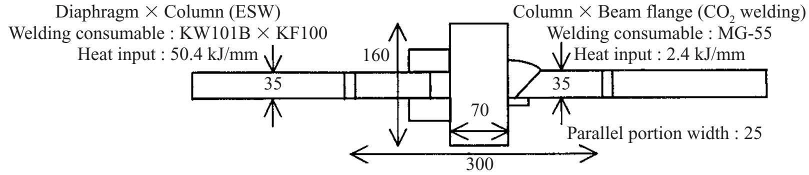
<table>
<tr><th rowspan="2">Thickness, t (mm)</th><th rowspan="2">Shapes and dimensions of groove</th><th rowspan="2">Welding conditions</th><th colspan="2">Tensile properties</th><th colspan="2">Charpy impact properties</th></tr>
<tr><th>TS (MPa)</th><th>Fracture positions</th><th>Notch position</th><th>$_{V}E_{0°C}$ (J)</th></tr>
<tr><td rowspan="4">35</td><td rowspan="4">
</td><td rowspan="4">Welding consumable : MG-55D
Heat input : 3.0 kJ/mm
Preheat : None
Inter pass temperature: ≦ 250°C</td><td rowspan="4">580
581</td><td rowspan="4">BM
BM</td><td>WM</td><td>157</td></tr>
<tr><td>FL</td><td>237</td></tr>
<tr><td>HAZ 1 mm</td><td>261</td></tr>
<tr><td>HAZ 3 mm</td><td>237</td></tr>
</table>

Table 6 Tensile test results of HBL385C's ESW and CO_2 welded joint

<table>
<tr><th rowspan="2">Welding method/Shape and dimensions of tensile test specimen</th><th colspan="2">Tensile results</th></tr>
<tr><th>TS (MPa)</th><th>Fracture positions</th></tr>
<tr><td rowspan="2">
</td><td>592</td><td>BM
(Beam flange)</td></tr>
<tr><td>599</td><td>BM
(Diaphragm)</td></tr>
</table>

Tensile strength was also the same as in the tests of the base material, demonstrating satisfactory welded joint strength in high heat input welding.

4.3 Features of High HAZ Toughness HBL385-E Steel Plate for High Heat Input Welding

HBL385C-E steel plate, in which the JFE EWEL technology is applied, is a high HAZ toughness steel for high heat input welding. Using samples of this material with thicknesses of 32, 40, and 50 mm, high heat input one-pass SAW and ESW were performed to verify material performance. The chemical compositions and mechanical properties of the sample plates are shown in **Table 7** and **Table 8**, respectively, and the welding conditions in the various cases are shown in **Table 9**. The obtained macrostructures are shown in **Photo 2**. The results of Charpy impact tests of these high heat input welding joints are shown in **Figs. 7–9**. In all of these welded joints, the average Charpy absorbed energy at 0°C shows high toughness of more than 70 J from the FL to the HAZ. Furthermore, Fig. 9 shows the ESW joint toughness under conditions of a small skin plate thickness/diaphragm thickness ratio, which corresponds to a CFT structure (concrete filled tube-structure welded box column). It can be understood that the welded joints under this condition display high toughness of more than 70 J (average) at 0°C.

Table 7 Chemical compositions of HBL385C-E

(mass%)

Thickness, t (mm)	C	Si	Mn	P	S	C_{eq}	P_{CM}	f_{HAZ}
32	0.12	0.28	1.54	0.007	0.001	0.40	0.21	0.36
40	0.11	0.28	1.54	0.007	0.001	0.40	0.21	0.35
50	0.11	0.28	1.54	0.007	0.001	0.40	0.21	0.35

Micro-alloying elements are added.

Table 8 Mechanical properties of HBL385C-E

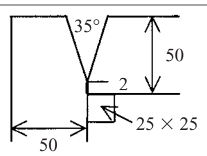
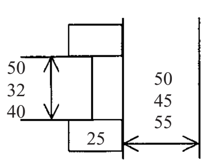
Thickness, t (mm)	YS (MPa)	TS (MPa)	El (%)	YR (%)	$_{V}E_{0°C}$ (J)	RA_Z (%)
32	472	602	33	78	361	83
40	473	604	32	78	346	84
50	446	570	33	78	346	81

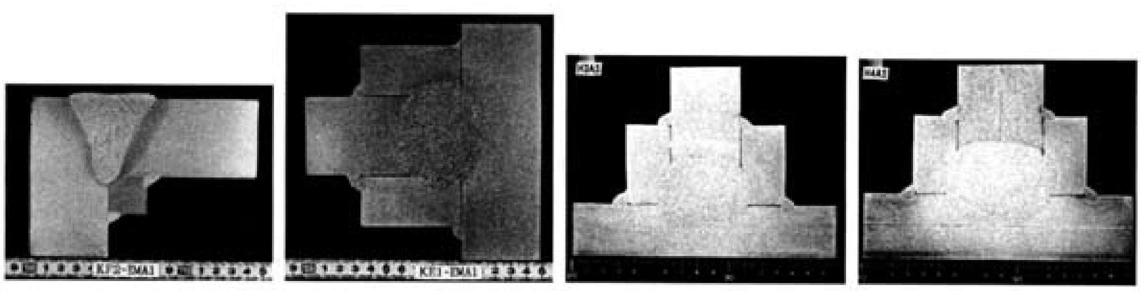
Tensile test : Full thickness (JIS No. 5)-C (32, 40t), 1/4t (JIS No. 4)-C (50 t)
Charpy test : 1/4t-C, RA_Z : Z

5. Conclusion

JFE Steel developed a high performance 550 MPa class high tensile strength steel plate for architectural construction, "HBL385" (lower yield strength value: 385 MPa) with new specified design strength, which offers a combination of economic efficiency, earthquake resistance, and weldability. This plate received the

Table 9 Welding conditions for HBL385C-E's SAW and ESW welded joints

Welding method	Shapes and dimensions of groove	Plate thickness (mm)	Thickness of diaphragm (mm)	Welding consumable	Welding condition	Heat input (kJ/mm)
SAW		50	–	KW-55 (6.4 mmϕ) × KB-60IAD	L : 1 850 A-43 V T : 1 500 A-50 V 210 mm/min	44.0
ESW		50	50	KW-60AD (1.6 mmϕ) × KF-100AD	380 A-53 V 15.0 mm/min	80.7
		32	45		380 A-48 V 19.5 mm/min	56.2
		40	55		380 A-51 V 15.8 mm/min	73.7



(a) SAW (50 mm) (b) ESW (SP : 50/DF : 50 mm) (c) ESW (SP : 32/DF : 45 mm) (d) ESW (SP : 40/DF : 55 mm)

Photo 2 Microstructures of HBL385C-E's SAW and ESW welded joints

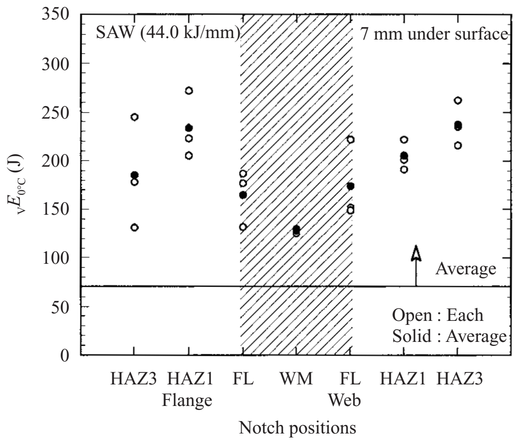


Fig. 7 Charpy impact properties of HBL385C-E's SAW welded joint (t = 50 mm)

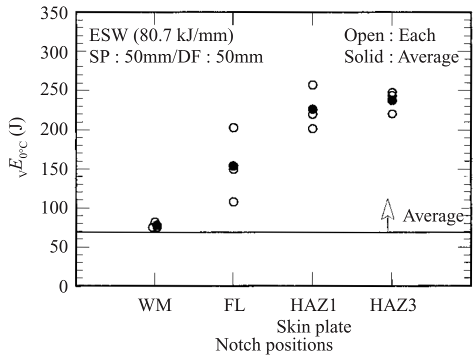


Fig. 8 Charpy impact properties of HBL385C-E's ESW welded joint (t = 50 mm)

approval of Minister of Land, Infrastructure and Transport under Article 37 of the Building Standard Low of Japan in April 2002, and has an increasing record of application in actual structures. JFE Steel is confident that the adoption of this new steel plate will give users an expanded degree of freedom in design and make it possible to respond to diversifying social needs.

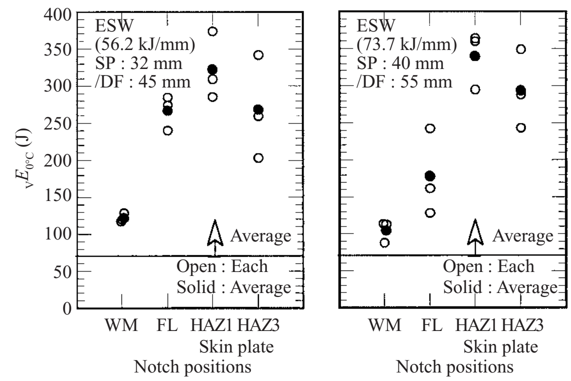


Fig. 9 Charpy impact properties of HBL385C-E's ESW welded joint for CFT structure

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