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High Performance 590 N/mm^2 Class Thermo-Mechanical Control Process (TMCP) Steel Plate "HBL™440" for Building Structure†

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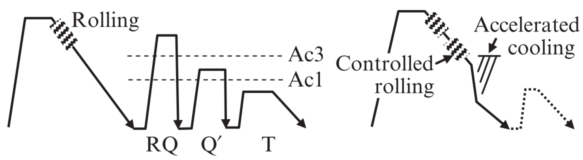
Abstract:

Conventional 590 N/mm^2 class steel for building structures, SA440, has been manufactured by a multiple off-line heat treatment processes involving intercritically reheated quenching, in order to achieve low yield ratio required for seismic resistance buildings. High performance 590 N/mm^2 class thermo-mechanical control process (TMCP) steel plate "HBL™440" for building structures, which can be manufactured without an intercritically reheated quenching, has been developed by applying the uniquely advanced JFE Steel's on-line accelerated cooling system. The developed steel plates from 19 mm to 100 mm in thickness satisfy the specification of SA440 and exhibit excellent weldability and high heat affected zone (HAZ) toughness in welded joints with very large heat inputs. Furthermore members fabricated with the developed steel plates have achieved equivalent plastic behaviors to those of SA440.

1. Introduction

Accompanying large spans in high-rise buildings and multistory design of commercial spaces, offices, hotels, etc. in recent years, heavy-wall and large-diameter specifications in steel frame columns have been progressively adopted. In the Landmark Tower in Yokohama (296.3 m), which was completed in 1993, large section box columns with a maximum 100 mm thickness × 900 mm square cross section were used[1)]. This trend has heightened the necessity of high-strength steels to hold down the weight increase due to the use of large section steel frame columns, and to reduce the environmental loads and costs in the various processes of steel manufacturing, steel frame processing, transportation, construction, etc.

Since Japan is an earthquake-prone country, absorption of energy by plastic deformation is also demanded in steel frame members of building structures in order to prevent collapse in large earthquakes. In many cases, a low yield ratio (low YR; YR = (Yield strength (YS))/(Tensile strength (TS))) of 80% or less is required in steel materials used in building steel frame members such as columns and beams. However, it is difficult to satisfy both high strength and low YR because YR generally increases with increasing strength of steel materials. In the heat-treated type 590 N/mm^2 class steel plate for building structures (SA440)[2)] developed in the 1990s, together with addition of large amounts of alloying elements, low YR was secured by multiple off-line



(a) Multiple heat treatment (Conventional steel)
(b) Thermo-mechanical control process(TMCP) (Developed steel)

RQ : Reheated quenching
Q′ : Inter-critical reheated and quenching
T : Tempering

Fig. 1 Manufacturing process of low yield ratio 590 N/mm^2 class steels

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heat treatment processes including inter-critical reheating and quenching, for example, as shown in **Fig. 1**(a). This complex heat treatment process lengthened the production period, while heavy addition of alloying elements reduced weldability; these factors were obstacles to expanded application of SA440.

JFE Steel secured mechanical properties equal to those of SA440 by a process that omits inter-critically reheated heat treatment, as shown in Fig. 1(b), by utilizing thermo-mechanical control process (TMCP) technology to build properties into the developed steel on-line, in other words, by a non-heat-treatment process. By combining TMCP with a proprietary high toughness technology for the heat affected zone (HAZ), JFE Steel developed a high performance 590 N/mm^2 class TMCP steel plate "HBL™440" for building structures that possesses both outstanding weldability and weld toughness in very high heat input welding. This product was approved by Japan's Minister of Land, Infrastructure, Transport and Tourism in August 2013 for the plate thickness range of 19–100 mm. This paper introduces the guidelines for achieving a low YR property and weld toughness in very large heat input welding, which are necessary properties in steel materials for building structures, simultaneously with high strength, and the basic performance of the base metal and welded joints of the developed steel, as well as the performance of members.

2. Basic Guidelines for Composition Design and TMCP

2.1 TMCP Technology for Low Yield Ratio

The basic guideline for achieving low YR in high strength steel is to produce a multi-phase microstructure comprising a soft phase and a hard phase. The combinations of soft and hard phases that can be used in 590 N/mm^2 class steels include ferrite + bainite, ferrite + tempered martensite, bainite + pearlite + martensite-austenite constituent (MA), etc. In realizing this kind of multi-phase microstructure by TMCP, it is necessary to optimize the chemical composition, controlled rolling conditions, and accelerated cooling conditions.

Figure 2 shows the influence of the accelerated cooling conditions on the microstructure of the developed steel by using a schematic continuous cooling transformation diagram (CCT diagram). Under condition (b), accelerated cooling is stopped at the proper temperature, and a bainite + pearlite + MA multi-phase microstructure like that shown in **Photo 1**(b) is obtained. As a result, the desired properties satisfying both adequate strength and a low YR property can be obtained. However, if the cooling stop temperature is too high, as shown by condition (a), the obtained microstructure is ferrite + pearlite, as shown in Photo 1(a), and strength is insufficient. On the other hand, if the cooling stop temperature is too low, as under condition (c), a high YR bainite single phase microstructure like that in Photo 1(c) will be obtained. **Figure 3** shows examples of the stress-strain curves of the low YR multi-phase microstructure in (b) and the high YR bainite single phase microstructure in (c). The existence of MA in the former simultaneously reduces YS and increases TS, and thus makes an especially large contribution to low YR.

Satisfying both high strength and a low YR property by controlling the microstructure to a multi-phase micro-

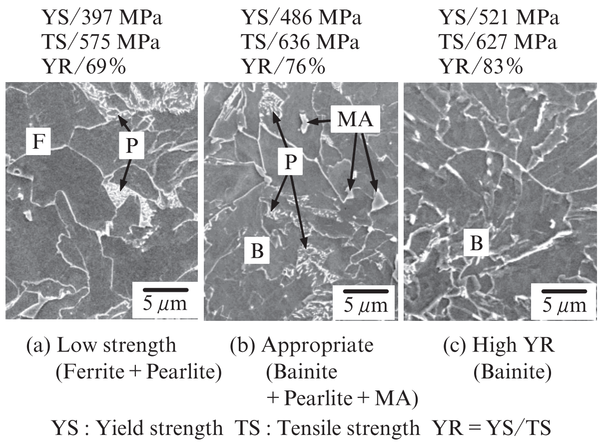


Photo 1 Examples of SEM micrographs

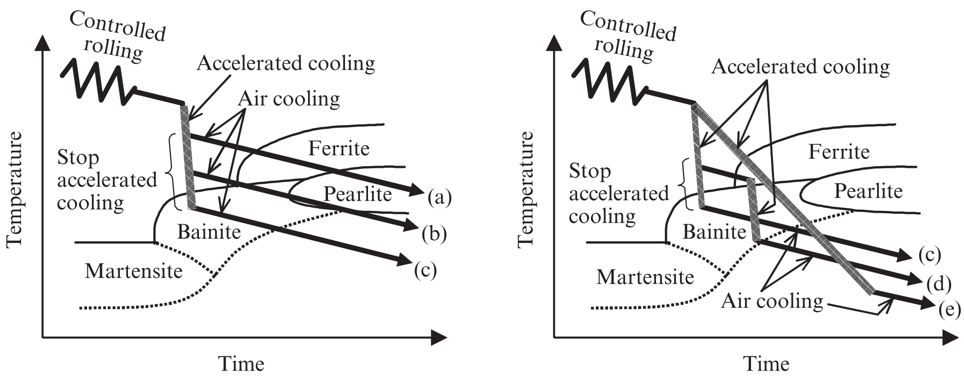


Fig. 2 Schematic illustrasions of controlling multi-phasemicrostructures with accelerated cooling

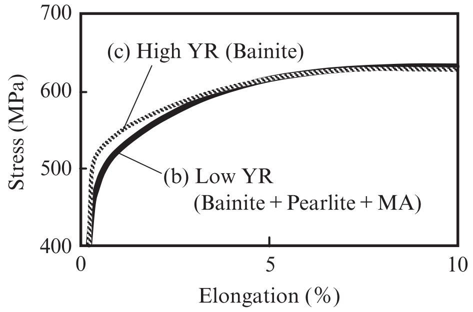


Fig. 3 Examples of stress-strain curves

structure can also be realized by interrupting accelerated cooling while in progress, as shown in Fig. 2(d), and thereby causing precipitation of ferrite, or by cooling rate control to cause ferrite precipitation during continuous cooling, as shown in (e). Moreover, as it is known that addition of alloying elements such as Mn, Cr, Mo, Nb, etc. increases MA formation[3], optimization of the addition of these alloying elements is also important.

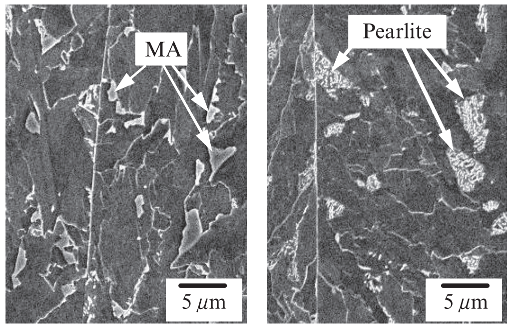
In the developed steel, proper microstructure and mechanical properties were achieved by utilizing JFE Steel's unique plate cooling technologies *Super*-CR[4] and *Super*-OLAC™ [5], which make it possible to apply highly precise and freely designed cooling patterns, and optimizing the addition of Cr, Mo, V, and Nb.

2.2 HAZ Toughness Technology for Very High Heat Input Welding

In the fabrication of welded built-up box columns for use as steel frame columns in high-rise buildings, very high heat input welding methods such as electroslag welding (ESW) and multi-electrode submerged arc welding (SAW) with heat inputs exceeding 500 kJ/cm are used, and as a result, remarkable embrittlement of the HAZ becomes a problem.

Heretofore, the basic methods for improving HAZ toughness in high heat input welding included the following: (1) Grain refinement of austenite (γ) by dispersing fine particles of TiN and carbides, etc. which are stable even at high temperature, (2) Reduction of hardenability by low C or low Ceq (including reduction of Nb), (3) Suppression of low toughness microstructure formation, such as upper bainite containing MA, by securing a HAZ microstructure comprising mainly ferrite with a comparatively low hardenability composition design, for example, by promoting the formation of intragranular ferrite in γ grains by utilizing fine dispersed particles[6].

In contrast to these techniques, in the developed steel, alloying elements such as Mo, etc. are added, and a composition design with somewhat higher hardenability than in the conventional approach is adopted in order to secure strength and achieve a low YR in on-line manufacturing. Therefore, to satisfy specifications which



(a) Conventional (0.25Si-0.010P) $vE_{0℃}$ = 13 J
(b) Developed (0.06Si-0.004P) $vE_{0℃}$ = 42 J
MA : Martensite-austenite constituent
$vE_{0℃}$: Absorbed energy at 0℃

Photo 2 Microstructures of synthetic heat affected zone (HAZ) simulating electroslag welding (ESW)

particularly require weld toughness in high heat input welding, such as materials for box columns, there was an orientation toward allowing the formation of upper bainite in the HAZ in high heat input welding, and suppressing the formation of MA in the upper bainite as far as possible. It has long been known that reducing the Si content reduces MA formation in the high heat input HAZ[7]. However, a further reduction in the MA content, and a resulting improvement in HAZ toughness, is possible by reducing P simultaneously with Si. **Photo 2** shows microstructure images of synthetic HAZ specimens after a heat cycle (heating to 1 400°C, cooling time from 800 to 500°C: 1 000 s) simulating the area of the bond in ESW joints with an heat input of 1 000 kJ/cm. MA can be observed in the SA440 with the conventional composition (high weldability SA440-U[8]), but in contrast, MA was remarkably reduced and changed to a pearlite microstructure in the low-Si, low-P composition in which Si and P were reduced simultaneously. Accompanying this, the toughness of the synthetic HAZ of the developed steel was improved, in spite of the fact that the main constituent of the microstructure is upper bainite.

3. Features of Developed Steel Plate

3.1 Base Metal Properties and Weldability

Table 1 shows the target range of the chemical composition of the developed steel (HBL™440 standard) and the compositions of steels tapped from the actual converter (product analysis) . In addition to suppressing weld low temperature crack sensitivity by reducing the C content to < 0.10%, elements such as Cr, Mo, V, Ti, etc. were added so as to obtain a microstructure comprising mainly bainite, which has an excellent balance of strength and toughness, in the base metal and high

Table 1 Chemical compositions of developed steels

	Thickness (mm)	Chemical compositions (mass%)						Ceq*1	P_{CM}*2
		C	Si	Mn	P	S	Others		
Developed steels	19	0.06	0.21	1.47	0.008	0.002	Cr, Mo, Nb, V, Ti	0.42	0.17
	25	0.06	0.21	1.45	0.010	0.002		0.41	0.17
	40	0.05	0.21	1.46	0.009	0.001		0.41	0.16
	50	0.05	0.21	1.47	0.010	0.001		0.41	0.16
	60	0.09	0.06	1.50	0.005	0.002		0.45	0.20
	80	0.09	0.07	1.46	0.004	0.002		0.45	0.20
	100	0.08	0.07	1.49	0.005	0.002		0.45	0.20
Target of HBL440	$t \leqq 40$	≦ 0.12	≦ 0.55	≦ 1.60	≦ 0.030*3	≦ 0.008	as necessary	≦ 0.44	≦ 0.22
	$40 < t$				≦ 0.020*4			≦ 0.47	

*1Ceq = C + Si/24 + Mn/6 + Ni/40 + Cr/5 + Mo/4 + V/14
*2P_{CM} = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B
*3HBL440B, *4HBL440C

Table 2 Mechanical properties of developed steel plates

	Thickness (mm)	Specimen	Tensile properties				Impact properties	
			YS (N/mm^2)	TS (N/mm^2)	YR (%)	El (%)	$vE_{0^\circ C}$ (J)	vTrs (°C)
Developed steels	19	JIS 1A	490	619	79	18	358	−95
	25		487	613	79	21	371	−65
	40		485	614	79	27	364	−45
	50	JIS 4	484	612	79	31	380	−105
	60		482	631	76	29	347	−50
	80		471	601	78	27	348	−85
	100		471	603	78	28	340	−80
Target of HBL440	$19 \leqq t \leqq 32$	JIS 1A	440 ～ 540	590 ～ 740	≦ 80	≧ 15	≧ 70	—
	$32 < t \leqq 40$					≧ 16		
	$40 < t \leqq 100$	JIS 4				≧ 20		

YS: Yield strength TS: Tensile strength YR = YS/TS El: Elongation
$vE_{0^\circ C}$: Absorbed energy vTrs: Charpy fracture appearance transition temperature

heat input HAZ. The above-mentioned low-Si, low-P composition was adopted in plates with thicknesses of 60 mm and greater, assuming application to box columns, as this composition design considers HAZ toughness in high heat input welding.

Table 2 shows the tensile strength and Charpy impact properties of the base metal of the developed steel plates. In all cases, the results satisfy the targets (HBL™440 standard). The Charpy fracture appearance transition temperature (vTrs) is less than −40°C, showing excellent toughness of the base metal.

Table 3 shows the results of a y-groove weld cracking test with a plate thickness of 100 mm. Cracking did not occur in a test with CO_2 arc welding (GMAW) without preheating (5°C). Weldability was greatly improved in comparison with the conventional SA440 standard ($P_{CM} \leqq 0.28$)[2], and the developed steel shows excellent weldability equal or superior to that of the high weldability type SA440 ($P_{CM} \leqq 0.22$)[8].

Table 3 Results of y-groove weld cracking test

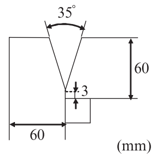
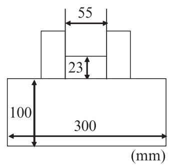
Thickness (mm)	Welding method	Test conditions		Cracking ratio (%)		
		Consumable Welding conditions	Pre-heating	Surface	Section	Root
100	GMAW (CO_2)	MG-60, ƒ1.2* 250A-30V-26 cm/min (17 kJ/cm) Atmosphere: 5°C, 60%	no (5°C)	0	0	0
				0	0	0

*Kobe Steel, Ltd.

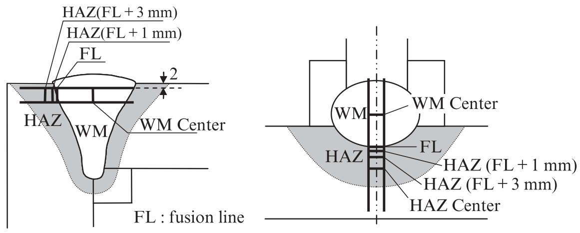
3.2 Properties of Welded Joints

High heat input welding joints were prepared by submerged arc welding (SAW) and electroslag welding (ESW), and a Charpy impact test was performed. The welding conditions and outlines of the joints are shown in **Table 4**, and the test specimen sampling positions and test results are shown in **Figs. 4** and **5**, respectively. Even very high heat input welding joints using a heat

Table 4 Welding conditions

Welding method	Thickness (mm)	Pre-heating	Groove shape	Consumable / Welding conditions	Heat input (kJ/cm)
Submerged arc welding (SAW)	60	no (17°C)		Wire (L) : KW-101B* Wire (T) : KW-101B* Flux: KB-55I* / (L) : 2 300 A-38 V (T) : 1 800 A-52 V 19 cm/min	572
Electroslag welding (ESW)	100	no (8°C)		Wire: KW-60AD* Flux: KF-100AD* / 380 A-52 V 1.2 cm/min	960

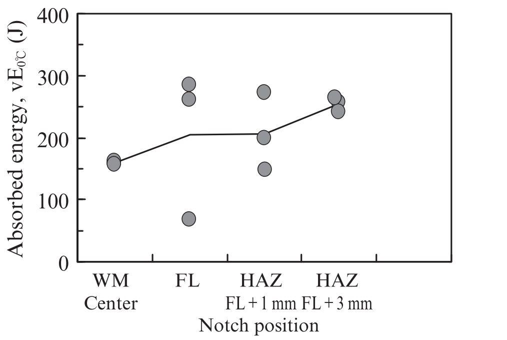
*Kobe Steel, Ltd.



(a) Submerged arc welding (SAW) joint (b) Electroslag welding (ESW) joint

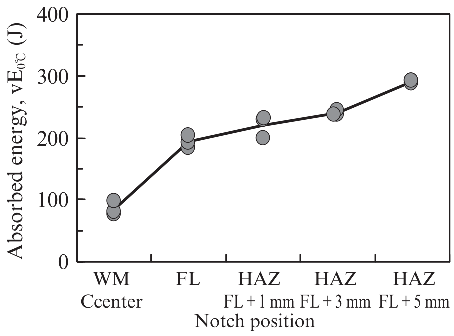
HAZ : Heat affected zone
WM : Weld metal

Fig. 4 Positions of Charpy impact test specimens for the welded joints



WM : Weld metal FL : fusion line HAZ : Heat affected zone

(a) Submerged arc welding (SAW) joint



(b) Electroslag welding (ESW) joint

Fig. 5 Results of Charpy impact tests for the welded joints

input of 500 kJ/cm or higher showed an excellent Charpy property with an average of 70 J or higher.

3.3 Member Performance

3.3.1 Local buckling performance

Inoue et al.[9] conducted stub-column compression tests of low YR 590 N/mm^2 class steel, which is considered to have become the SA440 standard thereafter. In this section, the results of a stub-column compression test of the developed steel HBL™440 and the results of the stub-column test by Inoue et al.[9] are compared, and performance against local buckling is discussed.

Figure 6 shows the outline of the stub-column test. Following the literature[10], vertical loading was applied in the vertical-downward direction so as to load the cross section uniformly.

Table 5 shows the details of the specimens. The specimens were stub-columns of welded built-up box columns. A total of two specimens were tested, and were set aiming at the FA-FB boundary and the FB-FC boundary. Both were actual size and were assembled using steel plates with a nominal thickness of 19 mm.

Figure 7 shows the plastic deformation magnification R_m obtained as a result of the test, together with the results for SA440[9]. Here, R_m is defined as follows:

$$R_m = \varepsilon_{max}/\varepsilon_y - 1$$

ε_{max}: Compressive strain ((Shortening of specimen)/(Initial height)) at maximum bearing force in experiment
ε_y: Yield strain (= σ_y/E)
σ_y: Yield strength of steel used in specimen (N/mm^2)
E: Young’s modulus (= 205 000 N/mm^2)

The equivalent width-thickness ratio, which is

Table 5 Specimens of stub-column test

Specimen	B (mm)	t (mm)	B/t	$(B/t)\ (\varepsilon_y)^{1/2}$	A (mm)	h (mm)	σ_y (N/mm²)	σ_u (N/mm²)	σ_y/σ_u	EL (%)
BOX 1	455.3	19	24.1	1.18	32 990	1367	495	621	0.80	43
BOX 2	512.2	19	27.1	1.30	37 296	1538	472	612	0.77	44

B: Width, t: Thickness, ε_y: σ_y/E, E: Young modulus = 205 000 (N/mm²), A: Area, h: Height,
σ_y: Yield strength, σ_u: Tensile strength, EL: Elongation, (σ_y, σ_u and EL are from coupon tensile test, JIS No. 5)

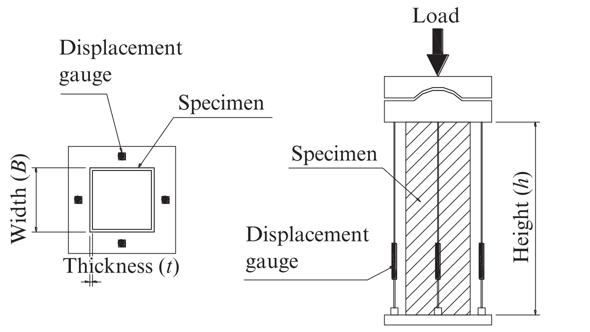


Fig. 6 Set-up of stub-column test

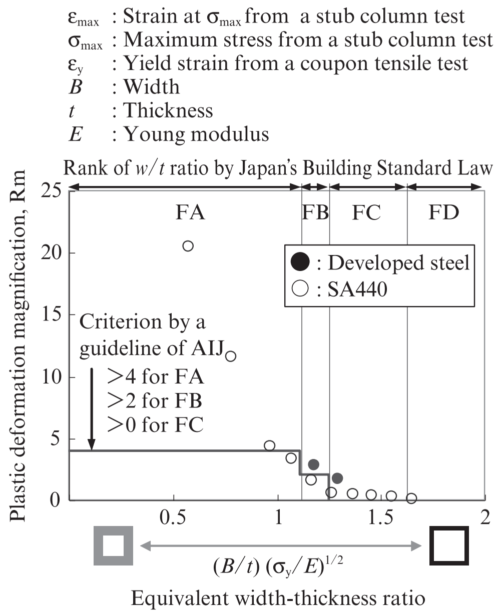


Fig. 7 Result of stub-column test

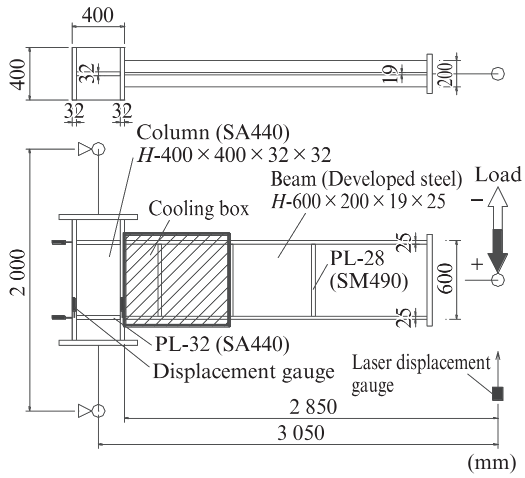
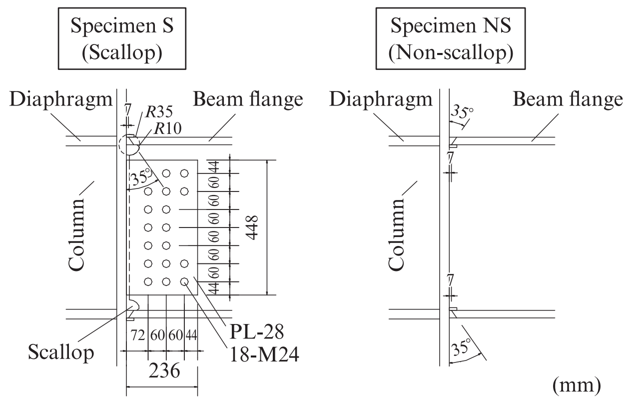


Fig. 8 Set-up of cyclic loading test of connection



Welding conditions of both specimens

Welding material :	JIS Z 3312 G59JA1UC3M1T
Heat input :	Not more than 30 kJ/cm
Interpass temperature :	Not more than 350℃
End tabs:	SM490A (Steel in JIS G 3106)

Fig. 9 Details of connections

obtained by multiplying the width-thickness ratio B/t by $(\sigma_y/E)^{1/2}$, is used on the horizontal axis, and shows the width-thickness ratio normalized by σ_y.

According to Fig. 7, it can be understood that the developed steel has performance equal to that of SA440. The developed steel also achieves the target value shown in “Recomendation for Limit State Design of Steel Structures[11].” Therefore, it is considered possible to set the index and width-thickness ratio rank, which govern local buckling, of the developed steel in the same manner as SA440.

3.3.2 Performance of beam-column connections

A cyclic loading test was performed in order to evaluate the structural performance of beam-to-column connections using the developed steel. The test set-up is shown in **Fig. 8**. Two specimens were tested. The experimental variable was the details of the connections, as shown in **Fig. 9**. That is, the specimen in which the beam web is joined with bolts and the beam flanges are made up by welding scallops is called the “field welding type,” and the specimen in which the web is fillet

Table 6 Mechanical properties of the developed steel plates for specimens of welded beam-to-column connections

Specimen	Column flange and web					Beam flange					Beam web				
	σ_y (N/mm²)	σ_u (N/mm²)	σ_y/σ_u	EL (%)	$vE_{0^\circ C}$ (J)	σ_y (N/mm²)	σ_u (N/mm²)	σ_y/σ_u	EL (%)	$vE_{0^\circ C}$ (J)	σ_y (N/mm²)	σ_u (N/mm²)	σ_y/σ_u	EL (%)	$vE_{0^\circ C}$ (J)
S (Scallop) / NS (Non-scallop)	499	641	0.78	48	316	494	631	0.78	47	290	496	630	0.79	43	379

σ_y: Yield strength, σ_u: Tensile strength, EL: Elongation, (σ_y, σ_u, and EL are from coupon tensile test, JIS No. 5)
$vE_{0^\circ C}$: Charpy absorbed energy at 0°C

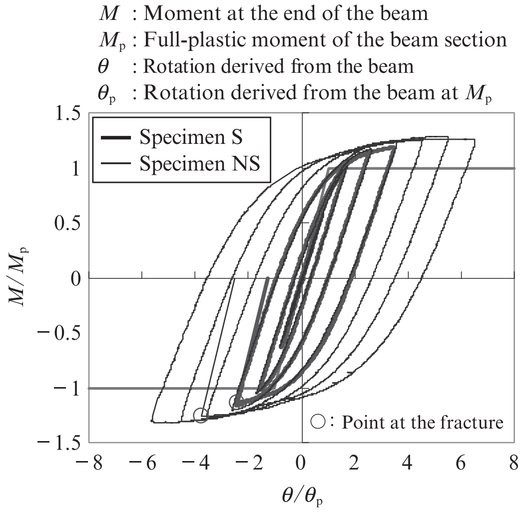


Fig. 10 Result of cyclic loading test of connection

welded and the flanges are welded without scallops is called the "shop welding type." In both specimens, the welding material JIS Z 3312 G59JA1UC3M1T (1.2φ) was used in welding the beam end flanges (JIS: Japanese Industrial Standards) . The heat input was controlled at 30 kJ/cm or less, and the interpass temperature was controlled at 350°C or less.

Welded H-shapes of the sizes shown in Fig. 8 were used in the columns and beams. The developed steel plate (Plate thickness: 19 mm and 25 mm) was used in the beams, which are assumed to fail. The mechanical properties of these steel plates are shown in **Table 6**. The developed steel has a yield ratio of less than 80% and high toughness of 290–379 J.

Figure 10 shows the relationship between the beam end moment and rotation angle, normalized by the value at full plastic moment. In specimen S with the scallop, a ductile crack with its origin at the slit between beam flange and the steel tab, and another ductile crack which initiated from the bottom of the scallop, grew as deformation proceeds, and brittle fracture occurred in a form in which these two cracks join. On the other hand, in the non-scallop specimen NS, a ductile crack initiated from the slit between the beam flange and the steel tab. After this crack grew following the HAZ, brittle fracture occurred to the base metal side.

The ductility factor (θ/θ_p) of specimen S is 3 or more, whereas specimen NS withstands deformation equivalent to a ductility factor of 6 or more. After plasticizing, both displayed large deformation, and proof stress increased by more than 15% from full plastic moment M_p.

These results are substantially the same performance as that in cyclic tests of beam-to-column connections of SA440[12–14] under the same conditions, and thus show that the developed steel has a high plastic deformation capacity.

4. Conclusion

In the developed steel "HBL™440," excellent weldability and mechanical properties satisfying the specification of the conventional 590 N/mm² class low YR steel plate for building structures, SA440, were realized by utilizing TMCP technology, while omitting off-line inter-critical reheating and quenching, which had been essential with SA440. Tests of steel frame members showed that members using "HBL™440" have performance equal to that of SA440. Application to building steel frame members such as welded built-up H-shapes, cold-press-formed square steel tubes (square steel tubes), circular steel tubes, welded built-up box columns, etc. is expected.

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