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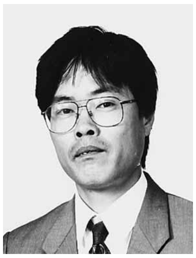
TS590 MPa Class Extremely-low Carbon Bainitic Heavy Gauge H-Shapes Having Excellent Weldability*



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Synopsis:

TS590 MPa class heavy gauge H-shapes having an excellent weldability have been successfully developed by applying an extremely-low carbon bainitic steel. The developed H-shapes have high strength and high toughness, which satisfies the SA440 specification without any heat treatment. Because the steel has excellent cold cracking resistance and low hardenability in heat affected zone, no pre-heating is required at welding. Column to column and column to beam welded joints, in which the developed steel was used as a column material, showed sufficient strength and toughness in terms of SA440 specification. The developed heavy gauge H-shapes under a brand name of "RIVER TOUGH 440" were applied to the highrise buildings as column materials at the HARUMI urban renewal project.

1 Introduction

Heavy gauge H-shapes with flange thicknesses exceeding 40 mm have a large cross section, comparable to that of box columns assembled from steel plates by welding, and are increasingly being used as column materials in high rise structures. This is because H-shape columns can improve efficiency of welding, and thus offer various advantages in comparison with box columns, including improved safety and shorter manufacturing period and quicker delivery. In recent years, Kawasaki Steel has developed thermomechanical control process (TMCP) type heavy gauge H-shapes,[1,2] which do not require a reduction in specified design strength (*F* value) accompanying the adoption of thicker flanges, and heavy gauge H-shapes with a flange width of 500 mm and web height of 700 mm, which is the world's largest web height,[3] thereby expanding the range of applications of H-shapes. The current limit on the strength level of H-shapes is a tensile strength of 520 MPa, and much higher strength is desired in order to expand application to column materials for high rise buildings and other uses with similar requirements.

As high-strength steel with a tensile strength exceeding 520 MPa for building structures, high performance 590 MPa structural steel for use in building frames (SA440B, C)[4] received the general approval of Minister of Construction of Japan in 1997. These materials are manufactured by applying double quenching and tempering heat treatment to steel plates. However, realizing high strength in heavy gauge H-shapes by applying a heat treatment process not only requires heat treatment furnaces for H-shapes exclusive use, but may also diminish the essential superiority of heavy gauge H-shapes such as quicker delivery and excellent cost competitiveness. For this reason, newly developed high performance heavy gauge H-shapes of the 590 MPa class should satisfy the desired performance in the as-rolled process without heat treatment such as quenching and tempering.

Focusing on extremely-low carbon bainitic steel, in which the carbon content is reduced to around 0.02 mass%, Kawasaki Steel has established a new technology for controling mechanical properties of steels and applied the technology to the development of as-rolled high strength steel plates of large thickness.[5,6] By applying this technology to controlling the mechanical properties of steels to manufacturing process of H-shapes, a high strength heavy gauge H-shapes with tensile strength of the 590 MPa class has been developed in the as-rolled condition.

This article describes the metallurgical features of the

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extremely-low C bainitic steel, and the base material performance, weldability and the performance of welded joints in the newly developed products.

2 Features of Extremely-low Carbon Bainitic Steel

The representative chemical compositions of SM490, which is generally used for welding structure, and extremely-low C bainitic steel are shown in **Table 1**. The continuous cooling transformation curves (CCT) of these steels are also shown in **Fig. 1**. In the SM490, the microstructure greatly changes from the constituents of martensite, bainite, and ferrite and pearlite, as the cooling rate becomes smaller. In contrast, it is a feature of extremely-low C bainitic steel that there is only small change in the microstructure when the cooling rate is changed. In cases of extremely large and small, cooling rate partial formation of $\alpha_B°$ (bainitic ferrite)[7] and α_q (quasi-polygonal ferrite)[7] can be observed, respectively. Under these conditions, the main microstructural phase is α_B (granular bainitic ferrite, also referred to as the extremely-low C bainitic microstructure in the following). Because the α_B microstructure is characterized by higher strength than the ferrite and pearlite microstructure, applying an extremely-low C bainitic steel makes it possible to realize high strength while also securing strength uniformity in the cross section, even in heavy gauge steel materials.

Moreover, the strength of extremely-low C bainitic steel can be controlled easily by changing the transformation temperature. **Figure 2** shows the relationship between the hardness and transformation starting temperature for 0.02 mass%C steels with various contents of alloying elements.[8] The hardness of the extremely-low C bainitic steel is determined directly by the transformation starting temperature, which in turn can be controlled by adjusting the contents of alloying elements.

Table 1 Chemical compositions of steels used

(mass%)

Steel	C	Mn	Cu	Ni	Nb	B
SM490 class steel	0.14	1.3	—	—	—	—
Extremely-low C bainitic steel	0.02	1.6	Micro-alloyed			

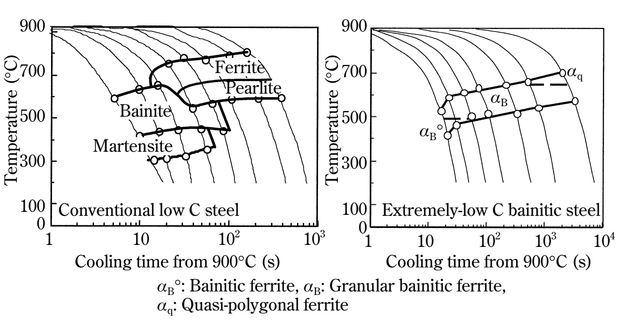


Fig. 1 Continuous cooling transformation curves (CCT) of SM490 and the extremely-low C bainitic steel

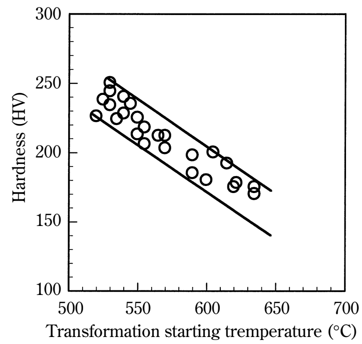


Fig. 2 Effect of the granular bainitic ferrite transformation starting temperature on hardness of the extremely-low C bainitic steels

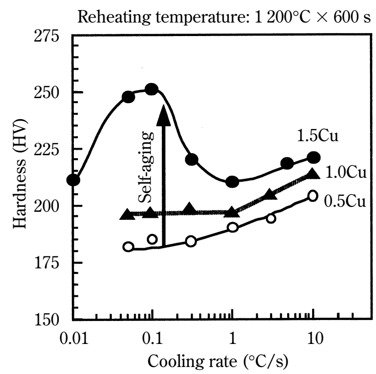


Fig. 3 Effect of Cu content and cooling rate after hot deformation on hardness of the extremely-low C bainitic steels

Furthermore, it is also possible to realize significantly higher strength in extremely-low C bainitic steel by combining transformation temperature control, as described above, with the self-aging of Cu. **Figure 3** shows the effect of the cooling rate on the hardness of extremely-low C bainitic steel having a C content of 0.02 mass% when the Cu content was varied in a range from 0.5 to 1.5 mass%.[8,9] In the comparatively low cooling rate condition, that is, at cooling rates of less than 0.3°C/s, softening is suppressed as the amount of Cu addition increases. In particular, 1.5 mass% Cu steel shows remarkable hardening at a cooling rate of 0.1°C/s. The fact that precipitation of Cu in the bainite phase can be observed, as shown in **Photo 1**, during cooling in this low cooling rate condition indicates that the behaviors described above are attributable to precipitation strengthening by Cu.

Traditionally, it was necessary to add large amount of alloying elements in order to realize high strength in heavy gauge H-shapes, but this causes increased susceptibility to cold cracking. Therefore, preheating was required before welding in order to prevent cold cracking of welds. In contrast, extremely-low C bainitic steel

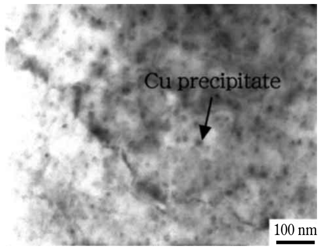


Photo 1 Typical TEM micrograph of 1.0 mass% Cu bearing extremely-low C bainitic steel after slow cooling with 0.1°C/s (thin film)

shows improved resistance to cold cracking because hardening at heat affected zone (HAZ) is minimized due to the extremely-low C composition. This means that a elimination of preheating (preheating-free welding)[6] can be expected with extremely-low C bainitic steel. Moreover, this steel also exhibited this remarkable effect even in non-steady welding, in which the cooling rate is extremely large, for example, at arc strike. Improvement in the toughness of the HAZ can also be expected to be improved due to a reduction in martensite-austenite constituents (M-A).[5]

In order to take advantage of the features described above, extremely-low C bainitic steel was applied in the development of the new high strength heavy gauge H-shapes.

3 Features of Developed H-Shapes

3.1 Chemical Composition

The typical chemical composition of the developed heavy gauge H-shapes is shown in **Table 2**. In terms of base material performance, the target for developed steel was to satisfy the standard for 590 MPa structural steels for use in building framing (SA440B, C).[4] In order to meet this requirement, the C content was set at 0.02 mass%, and the granular bainitic ferrite transformation temperature and softening resistance of the steel were adjusted by adding Cu and other alloying elements. Because it was possible to hold the carbon equivalent and weld cracking material parameter (Pcm) to 0.267% and 0.156%, respectively, improvement in weldability can also be expected. Slabs of this material were produced by basic oxygen furnace—RH degassing—continuous casting process. Intermediate rolling to beam blanks was performed by bloom rolling, followed by universal rolling to produce heavy gauge H-shapes with a web height of 582 mm, flange width of 510 mm, web thickness of 60 mm, and flange thickness of 65 mm.

3.2 Performance of Base Material

Table 3 shows the mechanical properties and Charpy impact values of the developed steel in comparison with the standard values of SA440. The developed heavy gauge H-shapes have high strength in the as-rolled condition, satisfying the standard value, and also amply satisfy the standard value for the Charpy impact property.

Photo 2 shows the microstructures of various portions of the developed steel. All parts show a granular bainitic ferrite microstructure (extremely-low C bainitic structure), with no observable differences in any portions shown here. **Figure 4** shows the cross-sectional hardness distribution at the 1/4 flange width area. The flange has a uniform hardness distribution, with virtually no variation in hardness in the thickness direction.

3.3 Susceptibility to Cold Cracking

In order to evaluate susceptibility to weld cracking, a y-groove weld cracking test was performed in accor-

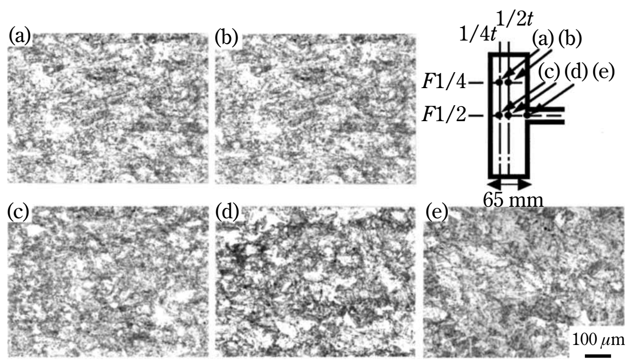


Photo 2 Microstructure of the developed H-shape at various portions

Table 2 Typical chemical composition of the developed H-shapes

(mass%)

C	Si	Mn	P	S	Al	Cu	Others	Ceq*	Pcm**
0.02	0.30	1.25	0.010	0.003	0.030	0.87	Ni, Nb, B, Ti	0.267	0.156

*Ceq = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14
**Pcm = C + Si/30 + Mn/20 + Cu/20 + Ni/60 + Cr/20 + Mo/15 + V/10 + 5B

Table 3 Mechanical properties at various portions of the developed H-shapes

Steel	Spec. and size	Portion	Direction	YP (0.2%YS) (MPa)	TS (MPa)	YR (%)	vEo (J)
	SA440	$F1/4$-$1/4t$	L	440–540	590–740	<80	>47
Developed H-shape	582 × 510 × 60 × 65 mm	$F1/4$-$1/4t$	L	487	636	77	212
		$W1/4$-$1/4t$	L	458	632	72	153

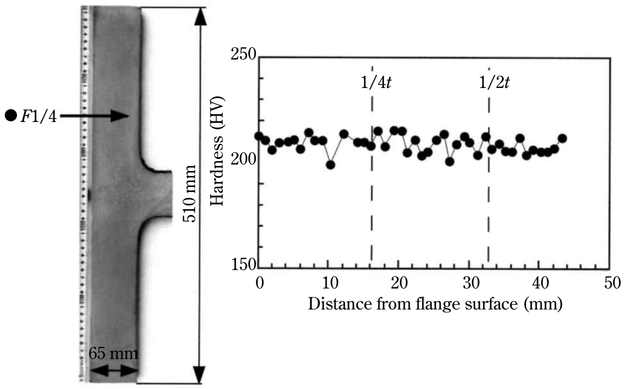


Fig. 4 Macrostructure and hardness distribution of developed H-shapes at flange portion

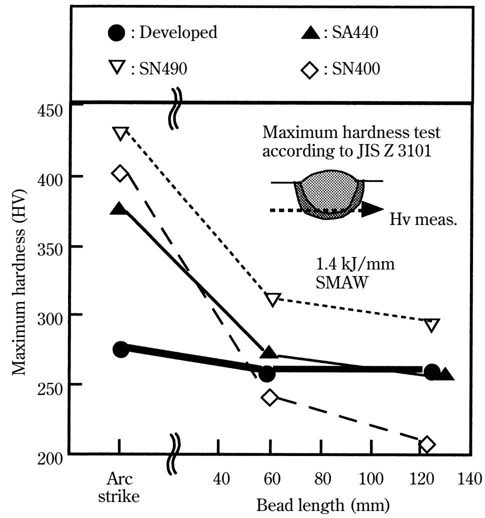


Fig. 5 Maximum hardness observed for unsteady-state welding of short bead length and arc-strike

dance with JIS Z 3158. Samples were taken from the 1/4 flange width area, and test pieces used in the experiment were prepared by decreasing the material thickness to 40 mm. The test conditions and results are shown in **Table 4**. Based on the fact that absolutely no cracking occurred, even at atmospheric temperature of 25°C, the manufactured heavy gauge H-shape has an even higher level of cold cracking resistance than the heat-treated type 590 MPa class steel plate (SA440).

3.4 Hardenability of HAZ

To investigate the hardenability behavior of the heat affected zone, a maximum hardness test of HAZ was performed in accordance with JIS Z 3101. In addition to the standard bead length of 125 mm specified in JIS, tests were also conducted with a bead length of 60 mm, in case of a short bead, and in an arc-strike condition with an arc time of 1 s, in a case of spot welding. The results are shown in **Fig. 5** in comparison with the heat-treated type 590 MPa class steel plate (SA440), steels SM440 and SN490. Because martensite formation is suppressed in the developed steel by reducing the carbon content to 0.02%, the effect of the bead length on hardness is extremely small. The maximum Vickers hardness under the arc-strike condition was also low, at 270 points, in comparison with 380 points for the SA440 plate, showing that the developed steel has excellent resistance to hardening of the HAZ.

4 Welded Joint Performance Tests

To study application to practical column materials, column to column and column to beam welding were performed under conditions which can simulate the method emplayed in practical welding and the performance of the joints was evaluated.

4.1 Welding Conditions

The joints were produced by using a semi-automatic CO_2 arc welding. The welding conditions and details of the welded joints are shown in **Table 5** and **Fig. 6**, respectively. In case of column to column joints, joints were made up by using the normal welding electrode, KC60 (JIS standard YGW21), for 590 MPa class steel. In the case of column to beam joints, an SN490B class H-shapes with a flange thickness of 28 mm was used as the beam material, and KC50 (JIS standard YGW11) was used as the welding electrode. The fabricated joints were measurement of the hardness distribution, joint tensile strength, and Charpy impact property at the weld metal (WM), bond (fusion line: FL), and HAZ 1 mm from the bond.

Table 4 Results of y-groove weld cracking test according to JIS Z 3158

Thickness (mm)	Welding electrode	Welding conditions			Pre-heat temperature (°C)	Cracking ratio (%)		
		Current (A)	Voltage (V)	Speed (mm/s)		Surface (%)	Cross section (%)	Root section (%)
40	JIS Z 3212 D6216 (KSA86) 4 mmϕ	170	25	2.5	25	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0
					50	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0

Table 5 Welding conditions for column to column and column to beam structures

Item	Welding	Method	Welding electrode	Preheating temperature	Inter-pass temperature	Current (A)	Voltage (V)	Travel speed (mm/s)	Heat input (kJ/mm)
Column to column	CO_2 gas welding	Multi-layer	JIS Z 3312 YGW21 (KC-60)	≧100°C	≧80°C	290	35	5.8	1.7
Column to beam and stiffener	CO_2 gas welding	Multi-layer	JIS Z 3312 YGW11 (KC-50)	≧100°C	≧80°C	330	35	5.0	2.3

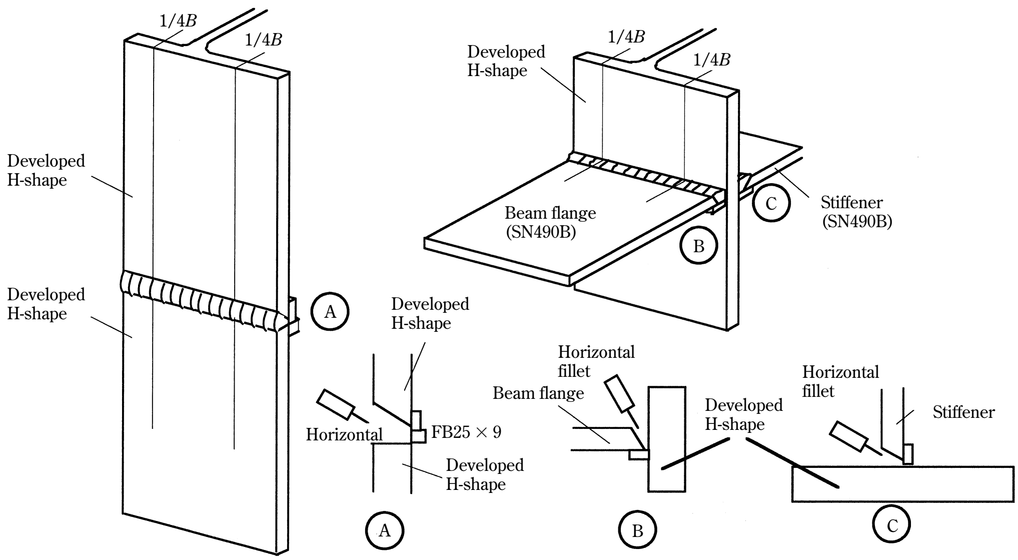


Fig. 6 Welding details of the column to column and the column to beam structures simulated by an actual construction method

4.2 Cross-sectional Hardness Distribution

The cross-sectional hardness distributions of the column to column and column to beam joints are shown in **Fig. 7**. No remarkable hardening or softening in HAZ was observed in the welded joints.

4.3 Tensile Test

The results of tensile test are shown in **Table 6**. In the case of column to column joints, the tensile strength was 631 MPa, and fracture occurred in the base material of the heavy gauge H-shape. In the column to beam joint, the tensile strength was 526 MPa, and fracture occurred in the base material of the beam (SN490B). These results confirm that column to column joints and column to beam joints of the developed H-shapes have sufficient strength when welding is performed using the actual welding method.

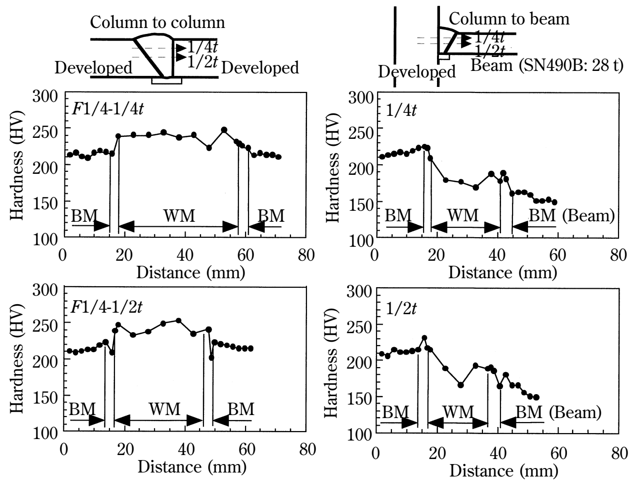


Fig. 7 Hardness distributions of the column to column and the column to beam joints

4.4 Impact Property

The results of Charpy impact test at the weld metal (WM), bond (FL), and HAZ 1 mm apart from the bond are shown in **Table 7**. In the column to column joints, test pieces were taken from the *L* direction relative to the flange surface of the heavy gauge H-shape, whereas, with the column to beam joints, test pieces were taken from the *Z* direction. At the bond and HAZ, the Charpy absorbed energies at 0°C were high, by amount of more than 200 J in both cases, indicating that these parts have sufficient toughness. Moreover, the Charpy value even in

Table 6 Tensile test results of welded joints

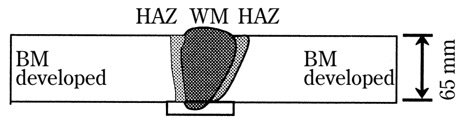
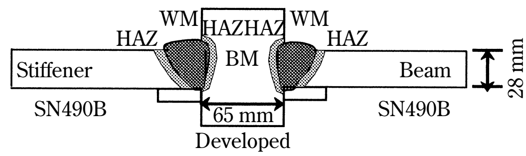
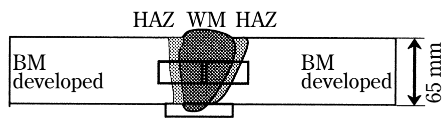
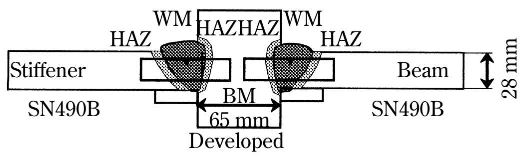
Item	TS (MPa)	Fracture position	Illustration of welded joints
Column to column	631	Column (Base metal)	
Column to beam and column to stiffener	526	Beam (Base metal)	

Table 7 Charpy impact test results of welded joints

	Position		Direction	V-Notch position	vE_0 (J)	Illustration of welded joints
Column to column	$F1/4B$	$1/4t$	L	HAZ	316	
			L	Bond	255	
			L	W.M.	143	
		$1/2t$	L	HAZ	339	
			L	Bond	242	
			L	W.M.	111	
	$F1/2B$	$1/4t$	L	HAZ	248	
		$1/2t$	L	HAZ	164	
Column to beam and stiffener	$F1/4B$	$1/2t$	Z	HAZ	286	
			Z	Bond	232	
			Z	W.M.	164	
	$F1/2B$	$1/2t$	Z	HAZ	263	

the WM was more than 100 J. No effect of the sampling direction could be observed (L direction in column to column joints, and Z direction in column to beam joints), showing that the joints possessed excellent toughness.

Based on these results, it can be concluded that the developed heavy gauge H-shapes provide satisfactory base material performance and joint performance for use as column materials in building structures.

5 Advantage in Building Structure Design and Application Experience

In the design of building structures, the sum of the stress ratios of the axial load and bending stress should be 1 or less.[10]), namely

$$\sigma_c/F_c + \sigma_b/F_b \leqq 1 \quad \cdots\cdots (1)$$

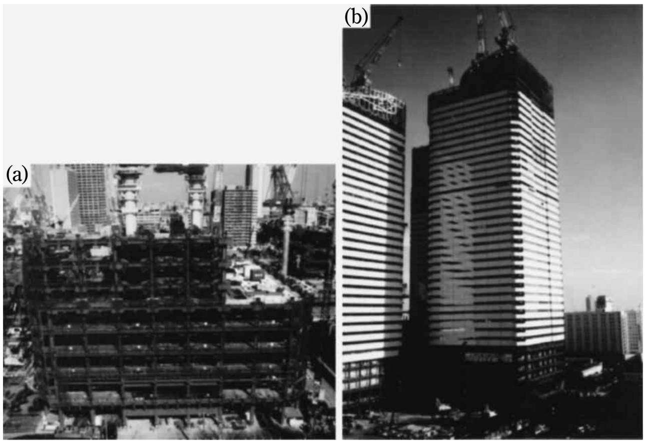
where, σ_c is average compression stress, F_c is allowable unit stress for compression, σ_b is average bending stress, and F_b is allowable unit stress for bending.

The specified steel strength, F value of steel materials when allowable unit stress is derived, is dependent on the yield strength of the steel material. Therefore, in contrast to the F value of 490 MPa class heavy gauge H-shapes, which is 3.3 t/cm^2 (325 MPa), the F value of the 590 MPa class heavy gauge H-shapes developed in this process is 4.5 t/cm^2 (440 MPa), or an increase of 36%. Among other design merits, the adoption of high strength column materials may reduces the stress ratios σ_c/F_c, σ_b/F_b due to an increase in the F value, and therefore allows builders to apply high strength H-shapes to the lower stories of high rise buildings. As a result, it has become possible to expand the range of applications of heavy gauge H-shapes in comparison with conventional ones.

Consideration of advantage of these features, the developed 590 MPa class heavy gauge H-shapes, under a trade name of “RIVER TOUGH 440”, were adopted for the first time in Japan as column materials for a high rise buildings in the Harumi 1-Chome urban renewal project (Triton Square) in Tokyo which are shown in **Photo 3**. In this project, Kawasaki Steel manufactured and delivered 1 300 t of the new H-shapes. In addition, 5 500 t of 490 MPa class TMCP heavy gauge H-shapes, RIVER TOUGH 325, which were developed by Kawasaki Steel in 1995, were also used.

6 Conclusions

Using extremely-low C bainitic steel, a new 590 MPa class heavy gauge H-shapes with extremely high weld-



(a) The lower layer structure using the RIVER TOUGH 440 as column materials
(b) The exterior of the renewal project

Photo 3 Construction landspcapes of the Harumi urban renewal project

ability have been successfully developed through the as-rolled process. The performance of the base material and joints of the developed steel are summarized as follows:

(1) The developed H-shapes have both high strength and high toughness, satisfying the standards for high performance steel (SA440) in the as-rolled condition even in a heavy gauge size of web height of 582 mm, flange width of 510 mm, web thickness of 60 mm, and flange thickness of 65 mm.
(2) The developed steel has excellent weldability, including extremely low susceptibility to cold cracking and hardenability of the HAZ under arc strike condition.
(3) Column to column joints and column to beam joints were fabricated under conditions which simulated the actual welding method, and their joint performance was evaluated. The results confirmed that joints of the new H-shapes have sufficient joint strength and toughness.
(4) The developed 590 MPa class heavy gauge H-shapes are commercialized as RIVER TOUGH 440 under Kawasaki Steel's own standard, and were adopted for the first time in Japan as column materials for a high rise buildings in an urban renewal project in Tokyo.

The authors wish to express their sincere appreciation to Sumitomo Corp. for its invaluable assistance in providing photographs of a structure in which RIVER TOUGH was used as column materials.

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