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Development of Application Technologies for Bridge High-performance Steel, BHS

Koji HOMMA*[1]
Mutsuto TANAKA*[2]
Kazumi MATSUOKA*[3]
Tadashi KASUYA*[3]
Hirofumi KAWASAKI*[2]

Abstract

BHS, Bridge High-performance Steels, produced by the recent advanced steel making technologies such as thermo-mechanical control process were developed. The BHS contribute to the economical design, efficient fabrication and higher performance of steel bridges. BHS has excellent properties such as high strength, high fracture toughness, good weldability, and ease of fabrication with the choice of weathering performance. This paper describes the proposed properties of BHS based on the required performance for bridge, the confirmed results of the basic properties of BHS and the merits of BHS in the design and fabrication of steel bridges.

1. Introduction

"Bridge high-performance steel" is defined as a steel material that is superior to conventional steel materials for bridge structures in terms of strength, fracture toughness, weldability, workability, and corrosion resistance, etc. which are required of bridges and that has its properties optimized for application to bridges[1)]. Thanks to the progress of thermo-mechanical process control technology in recent years, it has become possible to control the fine crystal structures in structural steel materials. As a result, remarkable improvements have been made in the strength, fracture toughness and other mechanical properties of structural steel. In addition, the weldability of structural steel has been markedly improved through optimization of the carbon equivalent and control of the weld crack sensitivity. It is expected that such performance-enhanced structural steel materials will be utilized positively.

The system of standards for steel materials for bridge structures is based on the Road Bridge Specifications published in the 1960s. In bridges to which the Road Bridge Specifications apply, therefore, steel materials which are compatible with the SM standards (JIS G 3106) are used as a rule. The system of standards for design and fabrication of steel bridges has been established so that the performance requirements of steel bridges are met even if steel materials which are barely compatible with the SM standards are used. Therefore, it is considered possible, for example, to design a steel bridge which is lighter in weight and higher in efficiency by using "bridge high-performance steel" that has higher strength and affords better weldability than those specified in the current SM standards and to make the fabrication of steel bridges more efficient by improving the weldability of the steel material used. This paper describes: 1) the performance requirements of bridge high-performance steel materials and the specifications required of those steel materials to meet the performance requirements, 2) confirmation of various performance requirements of the proposed bridge high-performance steel and verification of its workability, 3) example of the trial design of a steel bridge using bridge high-performance steel, and 4) an example of application of bridge high-performance steel to an actual project.

2. Newly Developed Bridge High-performance Steel (BHS)

Concerning bridge high-performance steel (BHS), the Society for the Study of High-Performance Steel Application Technology

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*[1] Construction & Architectural Materials Development & Engineering Service Div.

*[2] Plate Sales Div.

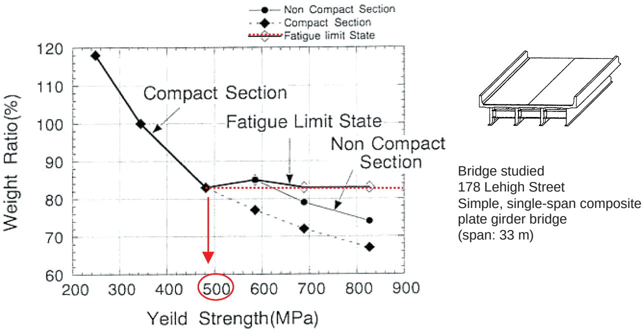
*[3] Steel Research Laboratories

established at the Creative Project Research Group in the Tokyo Institute of Technology has discussed the performance requirements of steel bridges and the specifications of steel materials for steel bridges as part of an industrial-academic joint project involving steelmakers and bridge fabricators[1]. In that project, before establishing the specifications of the new bridge high-performance steel, the author et al. studied the optimum yield strength of steel bridges and discussed various issues concerning the possibility of reducing the weight of steel structures, improving the reliability of welded structures, increasing the fracture toughness of steel structures, and improving the weldability and cold bending workability of steel materials, all through enhancement of the performance of steel materials[2-4].

With respect to the steel properties that improve the performance of bridges the authors first studied, the steel yield points that could effectively be applied to conventional plate girder bridges which are a most general structure of steel bridges[2-5]. **Fig. 1** shows the relationship between yield strength and weight of the main girder steel in an actual plate girder bridge, obtained from a trial design using the AASHOTO load and resistance factor design method with increasing the strength of the steel material used as the parameter. The study results show that with the increase in steel yield strength, the steel weight ratio decreases, but that when the yield strength exceeds about 500 N/mm^2, the fatigue limit state induced by the repeated vehicular live load becomes the factor governing the design. This suggests that for ordinary conventional steel plate girder bridges, increasing the steel yield strength beyond 500 N/mm^2 will not always be effectively used in design. After the above study, similar studies were conducted[6, 7]. Concerning girder bridges which account for the majority of steel bridges, the steel yield strength of 500 N/mm^2 is approximately the upper limit that can effectively be used. Therefore, it was proposed that 500 N/mm^2 be adopted as the basic yield strength for BHS[1, 8].

For suspension bridges and cable-stayed bridges–bridge types in which reducing the dead load of the superstructure has a significant effect on the bridge economics, 700 N/mm^2 was also proposed as the yield strength for BHS since high strength steel with a tensile strength of 780 N/mm^2 (yield strength: 680 N/mm^2) that was used in the Honshu-Shikoku Bridge proved effective[1, 8]. Eventually, standards for BHS (yield strength or proof stress, tensile strength, etc.) were set as shown in **Table 1**[9].

Improving the weldability of steel for bridge structures is important from the standpoint of enhancing the efficiency of bridge fabrication. In particular, conventional high strength steel of SM570 Class or higher requires preheating as a measure to restrain cold cracking. The need for preheating is one of the detrimental factors regarding efficient bridge fabrication. In order to impart both high strength and good weldability to BHS, the preheating process has been reduced or omitted by lowering the weld crack sensitivity (P_{CM}) that determines the need for preheating and the preheating temperature. As shown in **Table 2**, P_{CM} of BHS500/500W has been reduced to 0.20 so that the preheating process may be omitted.



Bridge studied
178 Lehigh Street
Simple, single-span composite plate girder bridge
(span: 33 m)

Fig. 1 Relationship between yield strength and steel weight in plate girder bridge

With respect also to the welding heat input for BHS500/500W, it has been raised from the upper limit of 7 kJ/mm per pass for the conventional SM570 steel to the 10 kJ/mm applicable to SM490 so as to permit welding with a large heat input in a smaller number of passes. Depending on circumstances, the heat input may be increased up to 15 kJ/mm.

In steel bridges, cold bending work on steel materials is applied to various members, including the main girders, towers, piers, floor slabs and steel pipe structures. This is one of the beneficial techniques employed in bridge fabrication. However, in applying cold working to steel, it is necessary to pay due attention to the embrittlement of steel due to strain aging. In fact, the Road Bridge Specifications set a certain limit on the minimum radius of cold bending work (as a rule, R=15 t) based on study results[3, 4]. For BHS, sufficient Charpy absorbed energy is secured (see Table 1) to permit bending work with a wider freedom of design and a smaller bending radius.

Among the members of a steel bridge, there are many joints which are subject to a through-thickness force. Therefore, in the development of BHS, consideration was given to its through-thickness characteristic as well. For BHS, the sulfur content that influences the resistance to lamellar tear was reduced to 0.006% or less, and as its through-thickness characteristic, the through-thickness reduction level Z35–the highest of the levels specified in JIS G 3199–was targeted.

In order to minimize the need of maintenance, weatherproof versions (BHS500W/BHS700W) have been added to both types of BHS (yield strength: 500 N/mm^2,700 N/mm^2) with the superior performances mentioned above.

Table 1 Yield strength, tensile strength and Charpy absorbed energy of BHS steels

Type code	Plate thickness (mm)	Yield strength (proof stress) (N/mm^2)	Tensile strength (N/mm^2)	Charpy absorbed energy (J)
BHS500 BHS500W	6≦t≦100	Min. 500	570-720	100 @–5℃*1
BHS700W	6≦t≦100	Min. 700	780-970	100 @– 40℃*2

*1 V-notch cut perpendicularly to rolling direction.
*2 V-notch cut along rolling direction.

Table 2 Weld cracking parameter (P_{CM}), preheating temperature condition and applicable heat input for BHS steels

Type code	Plate thickness (mm)	P_{CM}	Preheating temperature	Welding heat input (kJ/mm)
BHS500 BHS500W	6≦t≦100	0.20	Preheating not required	Max. 10
BHS700W	6≦t≦50	0.30	50℃	Max. 5
	50<t≦100	0.32		

3. Example of Application of BHS500

3.1 Performance of BHS base metal

In the Tokyo Nanboku Aqueduct, to which BHS was applied for the first time in Japan, about 1,200 tons of BHS500 steel 8 to 59 mm in thickness were used. The performances of those steels are described below. **Table 3** shows a typical chemical composition of BHS500. Thanks to the reduced phosphorus, sulfur, nitrogen, carbon and alloy contents, the weld crack sensitivity index (P_{CM}) is less than 0.20% (**Fig. 2**) and hence, the steel can be welded without preheating. **Fig. 3** through **5** show the measured mechanical properties of BHS500. In a tensile test, the yield strength of BHS500 was well above 500 N/mm². In a Charpy impact test, BHS500 exceeded the standard value of absorbed energy (100 J at –5 ℃) with a V-notch cut perpendicularly to the rolling direction, which is generally considered a more severe condition than one cut in the rolling direction. As the through-thickness characteristic required of the standard steel base metal, a percentage reduction of area of 35% or more is specified. In a reference test, it was confirmed that BHS met this requirement as well.

Table 3 Example of chemical compositions (%) of BHS500

	C	Si	Mn	P	S	V	N	P_{CM}
Standard	≦0.11	≦0.55	≦2.00	≦0.020	≦0.006	-	≦0.006	≦0.20
Actual	0.09	0.30	1.58	0.011	0.003	0.04	0.003	0.19

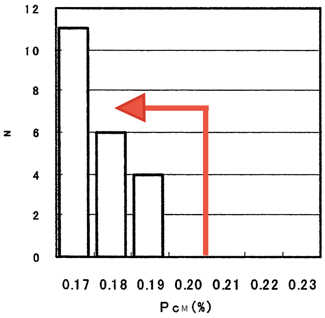


Fig. 2 Measured P_{CM} of BHS500

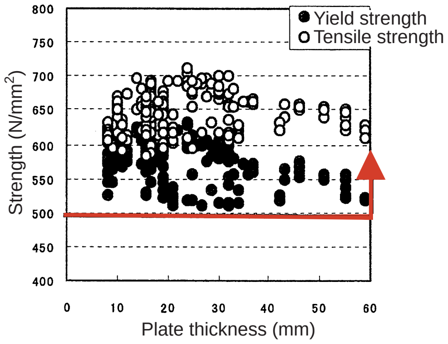


Fig. 3 Results of tensile test of BHS500

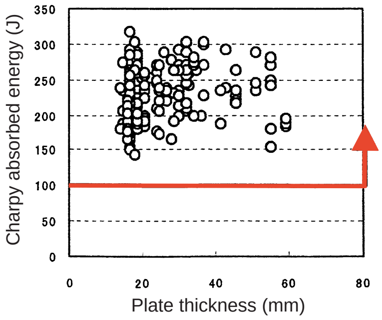


Fig. 4 Charpy absorbed energy at –5℃ of BHS500

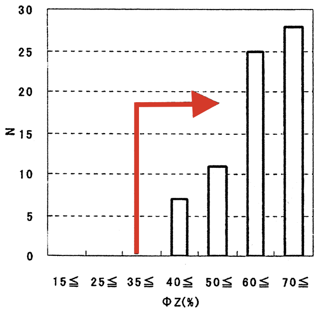


Fig. 5 Through thickness characteristics (percentage reduction of area, ϕ_Z) of BHS500

3.2 Workability of BHS500

While the BHS500 steel is very strong, it is as workable as SM490Y steel. This is one of the salient features of BHS500. It is known that when a steel material is subjected to cold working, the toughness of the steel deteriorates due to strain aging. The Road Bridge Specifications require that even after such aging, the required base metal toughness be met so that brittle fracture does not occur in the structure. The BHS steel is supposed to maintain its base metal toughness even after it is subjected to cold bending work with an inner bending radius equivalent to seven or more times the steel thickness which standard steel materials with a nitrogen content of 0.006% or less can withstand. In order to confirm those issues, a strain-aging test was conducted. The amount of strain applied to the test specimen was 10% (aging at 250℃ for 1 h), which is equivalent to a bending radius of 5 t. In the test, it was confirmed that the BHS steel completely meets the above requirement (**Table 4**).

The Road Bridge Specifications require that when gas flames are used to correct the strain in TMCP steel (Ceq = 0.38), the steel must be water-cooled or air-cooled immediately after the steel surface is heated to 900℃ or a lower temperature in order to prevent the steel toughness from deteriorating. In order to evaluate the features of

Table 4 Charpy absorbed energy after strain aging

Plate thickness (mm)	Amount of strain (%)	Charpy absorbed energy	
		V-notch	$_{V}E_{-5}$ (J)
40	0	Perpendicular to rolling direction	316
	10		298

Table 5 Results of line heating test

Plate thickness (mm)	Test conditions		Tensile test			Charpy absorbed energy (J)
	Temperature (℃)	Cooling	YP	TS	El	
			(N/mm²)		(%)	
40	900	Air cooling	534	637	30	293
	1,000		529	633	29	295
	900	Water cooling	536	637	28	295
	1,000		538	637	30	289

Table 6 Result of y-groove weld cracking test for BHS500

Plate thickness (mm)	Welding method	Welding material (diameter in mm)	Heat input (kJ/mm)	Ambient conditions Temperature (℃) Humidity (%)	Result (without preheating)
40	SMAW	L62CF (4.0)	1.7	20	No crack occurred
	GMAW	YM-60C (1.2)		60	No crack occurred

BHS steel manufactured with a low P_{CM}, a linear heating test at 1,000 ℃ was also conducted. As a result, it was confirmed that the mechanical properties of BHS satisfied the specified values (**Table 5**) and that the steel workability could also be improved in the straightening process.

The lowered preheating temperature is the most striking feature of the BHS steel. Since the P_{CM} of the BHS steel is lower than that specified in the Road Bridge specifications (0.20% or less), BHS does not require preheating for ordinary welding work. This was confirmed by the results of a y-groove weld crack test (**Table 6**).

3.3 Performance of BHS500 welded joints

From the standpoint of securing the required joint performance, the Road Bridge Specifications require that the welding heat input be 10 kJ/mm or less for the SM490 Class and 7 kJ/mm or less for the SM570 Class. That requirement was one of the factors that caused the workability of high strength steel to decline. Therefore, it was decided to improve the workability of BHS500 by making the allowable heat input comparable to that for the SM490 Class. On the other hand, the Standards for Honshu-Shikoku Bridge provide that the inter-pass temperature shall not be higher than 230℃. This requirement sets a limit on the workability of high strength steel. In the present development, the performance of BHS500 joints welded with large heat input was measured and at the same time, the welded joint performance was evaluated with the inter-pass temperature raised to 300℃, which is considered sufficient at the bridge fabrication stage (**Table 7**). The test results showed that BHS met the standards in terms of both strength (**Fig. 6**) and stiffness (**Fig. 7**). Thus, from the welded joint characteristics as well, it was confirmed that BHS steel had workability comparable to that of SM490.

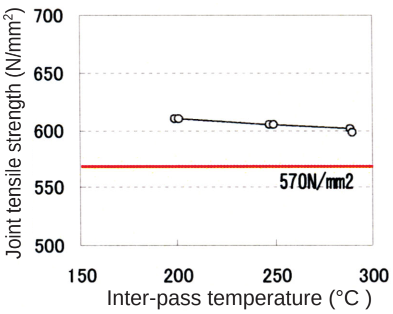


Fig. 6 Result of weld joint tensile test

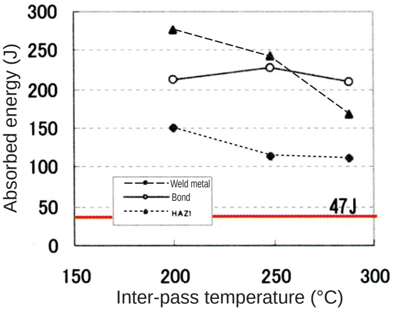


Fig. 7 Result of Charpy test for weld joint

4. Workability of BHS700W

Like BHS500, BHS700W is a steel material which can enhance the efficiency of bridge fabrication. It is stronger than BHS500 and is subject to a higher Charpy test temperature than BHS500. Because of this, for example, to prevent weld metal cracking, the preheating temperature for BHS700W is set at 50℃ and the maximum heat input is set at 5 kJ/mm. Tests for evaluation of BHS700W were carried out in the same way as those of BHS500. Of the test results, the workability of BHS700W is described below.

BHS700W is a steel material which Nippon Steel developed originally for the stiffening girders of the Akashi Kaikyo Bridge in 1994. The steel has low carbon content and has no boron added so as to lower the preheating temperature (from 120℃ to 50℃). In addition, the copper precipitation process is effectively utilized to secure the strength required of the steel[10, 11]. The guaranteed lower-limit yield

Table 7 Welding conditions for weld joint tests of BHS500

Welding method	Plate thickness (mm)	Welding materials		Maximum inter-pass temperature (℃)			Maximum heat input (kJ/mm)
		Wire (diameter, mm)	Flux	Aimed	Classification	Actual	
SAW	40	JIS Z 3351 YS-M5 Brand: Y-DM (4.8)	JIS Z 3352 FS-FG3 Brand: NF-320 32×D	200	1st	198	9.3
					2nd	200	10.0
				250	1st	248	9.3
					2nd	248	10.0
				300	1st	288	9.3
					2nd	288	10.0

Table 8 Example of chemical compositions (%) of BHS700W

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	P_{CM}
Standard	≦0.14	≦0.50	≦2.00	≦0.015	≦0.006	0.30≦	0.30 / 2.00	≦0.80	≦0.60	≦0.05	≦0.005	≦0.32*
Actual	0.06	0.26	1.30	0.004	0.001	1.13	1.46	0.59	0.44	0.04	0.0002	0.28

*: t > 50

Table 9 Mechanical properties of BHS700W

Plate thickness (mm)	Tensile test			Charpy absorbed energy (V-notch in rolling direction) (J)	Through-thickness reduction of area (%)
	YP (N/mm²)	TS (N/mm²)	El (%)		
60	782	820	24	245	54

Table 10 Charpy absorbed energy after strain aging

Plate thickness (mm)	Strain (%)	Charpy absorbed energy	
		Direction	$_vE_{-40}$ (J)
60	0	Rolling direction	245
	11		185

Table 11 Results of line heating test for BHS700W

Plate thickness (mm)	Conditions		Tensile test			Charpy absorbed energy (J)
	Temperature (℃)	Cooling method	YP (N/mm²)	TS (N/mm²)	El (%)	
60	900	Air cooling	785	827	25	250
	1,000		768	827	24	269
	900	Water cooling	783	830	23	251
	1,000		780	833	24	255

strength of the steel has been increased by 15 N/mm² by making the most of the manufacturing process by which the company had produced some 4,200 tons of BHS.

BHS700W was manufactured based on the composition design concept mentioned above. The typical chemical composition of the steel is shown in **Table 8**, and the principal mechanical properties of the steel are shown in **Table 9**. It can be seen that BHS700W offers the targeted performance. Concerning the workability (flexural characteristic), it was confirmed from a strain-aging test that the steel displayed sufficient performance even under a strain corresponding to a bending radius of 5 t (t: plate thickness) (**Table 10**). In a linear heating test, BHS700W, like BHS500, showed minimal deterioration even under the conditions of 1,000℃ and water-cooling (**Table 11**). With respect to the preheating temperature as well, it was confirmed that BHS700W was devoid of weld metal cracking when preheated at 50℃ (**Table 12**).

5. Trial Design of Steel Bridge Using BHS

The authors test-designed a steel bridge applying BHS and discussed the merits of using the BHS steel. The steel girder cross section was decided based on the assumption that a continuous composite girder bridge with a span length of 60 m was to be designed. In the trial design, ordinary steel (SM570 specified in the Road Bridge Specifications) was also used for the purposes of comparison.

Fig. 8 compares yield strength between SM570 and BHS500. The external dimensions of the test-designed bridge are shown in **Fig. 9**. Discussions were made in the following two ways.

1) Using the continuous composite girder design program based on the allowable stress-based design method described in the Road Bridge Specifications, the bridge cross section was designed assuming the allowable stresses of BHS500 and BHS700W as shown in **Table 13**. Since no allowable stresses are set for the BHS steels, it was assumed that the safety factor of allowable tensile stress was 1.75 for BHS500 (comparable to the safety factor for SM570) and 1.97 for BHS700W (comparable to the safety factor for HT780).

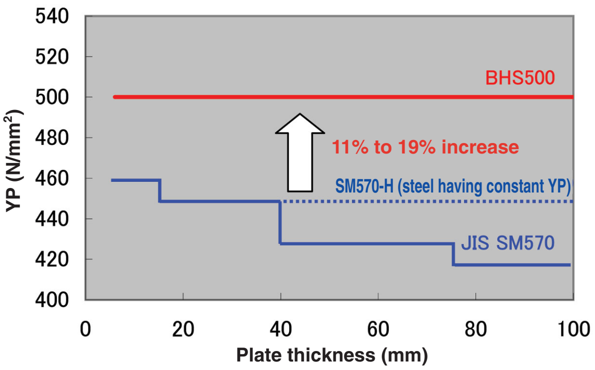
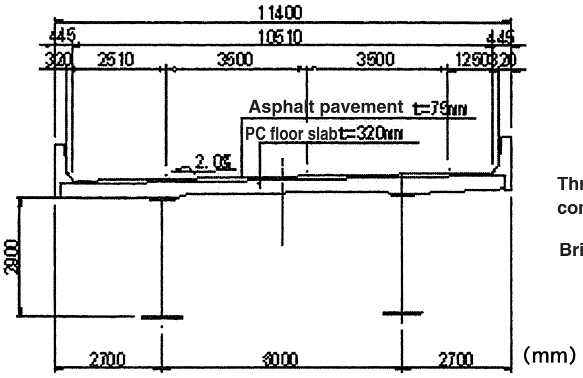


Fig. 8 Comparison of yield strength between SM570 and BHS500

Table 12 Result of y-groove weld cracking test for BHS700W

Plate thickness (mm)	Welding method	Welding material (diameter, mm)	Heat input (kJ/mm)	Ambient conditions Temperature (℃) Humidity (%)	Test results	
					Without preheating	Preheating at 50℃
60	SMAW	L80EL (4.0)	1.7	20	17% (weld metal)	No cracks occurred
	GMAW	YM-80C (1.2)		60	No cracks occurred	No cracks occurred



Three-span bridge having 2 main continuous composite girders

Bridge length: 180 m Span length: 60 m × 3

Fig. 9 Dimension of bridge for trial design

Table 13 Assumption of allowable stresses for BHS

		Unit	BHS500	BHS700W
Reference yield strength	σ_y	N/mm^2	500.0	700.0
Allowable tensile stress	σ_{ta}	N/mm^2	285.0	355.0
Safety factor	σ_y / σ_{ta}	-	1.75	1.97
Allowable shear stress	τ_a	N/mm^2	160.0	200.0

Table 14 Resistance factors

Type of resistance	Resistance factor ϕ
For flexure	$\phi_f = 1.00$
For shear	$\phi_v = 1.00$
For axial compression	$\phi_c = 0.90$

Table 15 Load factors

	Load combinations and load factors						
	Load factors						
Limit state	DC	DW	LL	IM	CR	SH	TU
Strength I	1.25	1.50	1.75	1.75	-	-	-
Service II	1.00	1.00	1.30	1.30	1.00	1.00	1.00
Constructibility	1.00	-	-	-	-	-	-

Table 16 Study case

	Material	Extra man-hour factor
Case 1	SM570	1.28
Case 2	BHS500	1.00
Case 3	BHS500	1.28
Case 4	BHS700W	1.28

2) Based on the limit state-based design method (AASHTO-LRFD), the ultimate limit state and normal limit state were checked using the load and resistance factors shown in **Tables 14 and 15** to design the bridge cross section.

Based on the methods described above, comparisons were made as to the consumption of steel materials and the total cost of construction with reference to the relevant data of the Ministry of Land, Infrastructure and Transport. Examples of the results of calculations of the quantitative merits of the BHS steels are given below.

Since the extra construction man-hours required by SM570 relative to BHS were unknown, the calculations for comparisons were made in four cases, including two cases using factor 1.00 for SM490Y and factor 1.28 for SM570 (**Table 16**).

1) When BHS500 or BHS700W, which is stronger than SM570, is used in place of SM570, the total weight of the steel material required decreases. According to the allowable stress-based design method, the decrease is about 7% when BHS500 is used and about 15% when BHS700W is used.
2) In terms of the cost of construction (material cost), BHS500 is the most advantageous (see **Table 17**). By using BHS500, it is possible to cut the construction cost by 4% in Case 3 and by about 10% in Case 2. **Fig. 10** shows the construction cost in each of the four cases in terms of ratio to Case 1 (= 1.00).
3) When BHS500 is used, it is possible to reduce the plate thickness of the upper and lower flanges by a maximum of 19% as compared with when SM570 is used. Thus, it is considered that BHS500 will help cut the cost of welding and improve the accuracy of nondestructive inspections of steel materials, especially thick ones.
4) According to the limit state-based design method (AASHTO-LRFD), the total weight of the steel material required for the sections that are subject to negative bending moments is nearly the same as in allowable stress-based design under the conditions

Table 17 Comparison of steel weight and total construction cost

	Case 1 SM570 (YP = 450N/mm²)	Case 2 BHS500 (YP = 500N/mm²)	Case 3 BHS500 (YP = 500N/mm²)	Case 4 BHS700W (YP = 700N/mm²)
Steel weight	1.00	0.93	0.93	**0.85**
Cost (material)	1.00	**0.90**	0.96	0.99

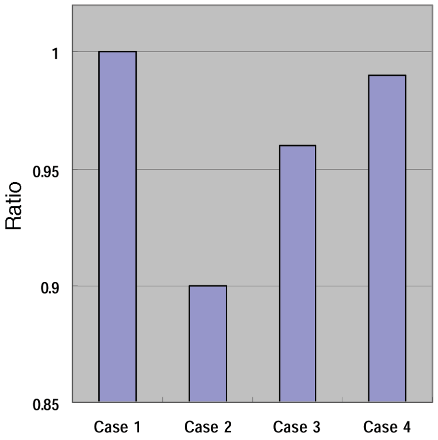


Fig. 10 Comparison of total construction cost

mentioned above. For the sections that are subject to positive bending moments, however, the total steel weight can be further reduced by 10% as compared with when the allowable stress-based design method is applied. The reduction of the steel weight of the superstructure contributes much to the cutting of the cost of the substructure. However, it was left out of consideration in the present estimations.

6. Application of BHS in Tokyo Bay Coastal Highway Project[12)]

BHS was adopted for bridges on the Tokyo Bay Coastal Highway (4.6 km section from the reclaimed ground outside the Central Breakwater in Koto-ku, Tokyo to Wakasu). The bridge spanning the Nanboku Channel (ordered by the Tokyo Metropolitan Government) is a three-span, continuous box girder bridge with a steel plate floor having a length of 256 m and a center span of 100 m. The total weight of the steel materials used for the bridge is 3,988 tons, 29% (1,143 tons) of which is BHS500. Tokyo Bay Coastal Highway Bridge (tentative name) (ordered by the Ministry of Land, Infrastructure and Transport)—the main bridge spanning the No. 3 Course—is a truss-box composite construction having a length of 760 m and a center span of 440 m (see **Fig. 11**). The total weight of the steel materials used for this bridge is 20,250 tons, 51% (10,250 tons) of which is BHS500. According to the Ministry of Land, Infrastructure and Transport, the use of BHS500 will reduce the total weight of steel materials for the Tokyo Bay Coastal Highway Bridge by 3% and cut the total cost of construction by 12%. In the Tokyo Bay Coastal Highway Project as a whole, about 43,000 tons of steel (including about 16,000 tons of BHS) are due to be used. It is expected that the BHS steel will help cut the total project cost significantly.

7. Conclusion

Nippon Steel has developed bridge high-performance steel (BHS) with the aim of contributing to economical design and efficient construction of steel bridges by enhancing the performance of steel materials. This paper discussed the performance requirements of steel materials for bridges, the development and production of the BHS steels that meet those requirements, and the advantages of the BHS steels including their economical merits. In the future, with the cooperation of all the organizations concerned, the authors intend to establish technological foundations for the design and fabrication of steel bridges using BHS and thereby contribute to the construction of economical, high-quality steel bridges.

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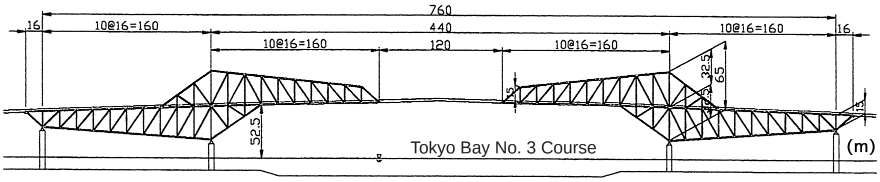

Fig. 11 Dimensions of Tokyo-bay coastal highway bridge