

ADVANCEMENT AND APPLICATIONS OF JAPANESE HIGH PERFORMANCE STEEL IN STRUCTURAL ENGINEERING

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ABSTRACT: Applications of steel to building structures in Japan can date back to the first steel factory, Shueisha Printing Plant, constructed in 1894. History of steel bridges in Japan can trace back to the first steel bridge, Kurogane Bridge in Nagasaki, constructed in 1868 using wrought iron. As the developments of large-scale structures, new construction technologies and demanding structural performance, a variety of high performance steels (HPSs) have been developed. In this study, history of applications of HPSs to building and bridge structures in Japan is briefly reviewed. The characteristics of typical HPSs in both buildings and bridges are introduced, respectively, and their impacts on structural engineering are also discussed.

Keywords: Steel, high performance, toughness, welding, ductility, weathering, buildings, bridges

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1. INTRODUCTION

Constructions of large-scale and large-span structures in developed countries tend to decrease in recent decades, and structural scales of most projects are becoming smaller in countries such as Japan and America. As a rival of reinforced concrete structures, steel structures are confronting a more and more competitive situation. Partially motivated by this concern, a number of high performance steels (HPSs) have been proposed to reduce construction cost, and employed in both building and bridge structures. As progress of new design concepts, connection details, fabrication technologies and mechanics, various properties such as higher strength, ductility, weldability, toughness, weathering and fireproofing properties, are increasingly demanded in practice. For example, design concept based on whole life cycle cost (LCC) is gaining more attention in steel bridges [1], which not only considers initial construction cost, but also maintenance expenses. From the viewpoint of LCC, durability related characteristics, such as weathering and fracture-resistant properties, are becoming more important issues for structural steels.

Before discussion on HPS, its definition is distinguished in different countries. In the USA, HPS is defined as having an optimized balance of strength, weldability, toughness, ductility, corrosion resistance and formability, to achieve the best overall performance of structures while remaining cost-effective [2-4]. A series of HPSs, HPS50W, HPS70W and HPS100W, were developed for steel bridges [3], where the aforementioned material properties are all considered through new manufacturing technologies including developments in metallurgical, rolling and heat-treatment. On the other hand, HPS in Japan commonly represents steels that have one or several virtues in strength, ductility, fire-proofing, weathering, weldability, toughness, cold formability, connecting feasibility [5, 6], etc. Therefore, the definition of HPS in Japan is broader than that in the USA, and there are more steel grades for HPS in Japan. In this study, Japanese HPSs developed respectively

for building and bridge structures are introduced in terms of specific properties, such as strength, toughness, weldability, connection feasibility, durability properties etc.

2. HIGH PERFORMANCE STEELS IN BUILDING STRUCTURES

2.1 General Comments

It is commonly acknowledged that performance of a high-rise building structure is governed by serviceability considerations such as inter-storey drift, which is mainly related with stiffness of a material, boundary conditions (connection stiffness), structural systems and loading conditions. As it is known that steel has a stable elastic modulus, currently it is still not possible to increase its value. It is thus considered not economical to increase strength of a structural steel for common structural systems. However, it is still promising to employ high strength steels in building structures when new structural systems are proposed [7].

In addition, most of past design specifications mainly focus on tensile strength properties, with some attention paid to ductility, fracture-resistant and weldability properties. The aforementioned properties were once deemed good enough to guarantee favorable performance for serviceability, capacities and ductility. However, recent strong earthquakes such as the 1994 Northridge earthquake [8, 9] and the 1995 Kobe earthquake [10, 11] shake this confident belief in steel welded moment resisting frames, especially for the connections details and fracture-resistant properties of the steels and welding materials. The catastrophic consequences of the earthquakes arouse an extensive research on fracture mechanisms of steel welded structures [12-18], and more attentions are paid to fracture-resistant and weldability properties of steels [19, 20]. As the development of new structural systems, fireproofing properties, connecting feasibility and energy dissipation capacity become more and more important in practice.

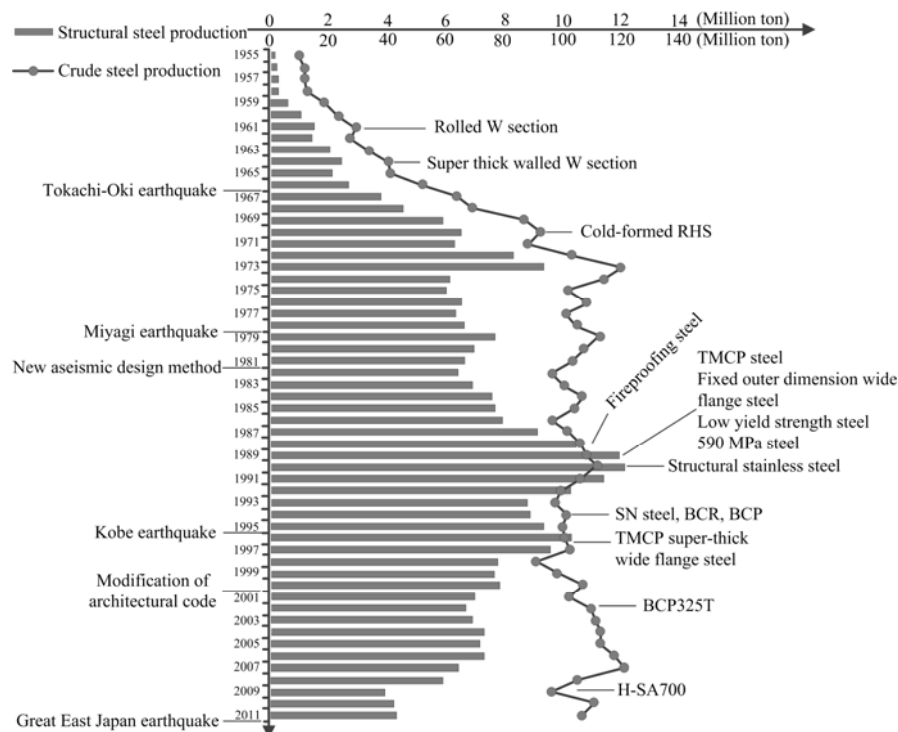


Figure 1. History of High Performance Steel in Building Structures (adapted from [21])

The Japanese crude steel and structural steel productions for building structures from the year of 1955 to 2011 are both plotted in Figure 1 [21], indicating that the structural steel production has passed its peak, while the crude steel production in recent forty years are quite stable. To promote application of steel structures, more economical structural systems, steels and corresponding manufacturing and connecting technologies are required. Strong earthquakes occurred in Japan are also marked in the figure, and a number of HPSs were developed as advancement in seismic design methods and steel manufacturing technologies etc.

2.2 Strength Related HPSs

2.2.1 SN, BCR and BCP

Before 1994, structural steels employed in buildings are SS (S: steel; S: structure) and SM (S: steel; M: Marine) series, which are also simultaneously employed in bridges and marine structures. Under the specific considerations of seismic design of building structures, deviations in the yield strength, tensile strength and yield-to-tensile strength ratio (YR) are of significant importance in the failure mechanisms of common frame structures [22]. To achieve better seismic performance and material weldability, a new series of HPS is developed for steel building structures in 1994, termed SN (S: steel; N: new) series [23]. Two corresponding series for cold formed rectangular hollow sections, BCR (box column-roll) and BCP (box column-press), are also developed, which have equivalent properties as those of the SN series. Mechanical and chemical properties of the SN steels are listed in Table 1. The SN steels has three types, A, B and C, and BCP steel has two types, B and C. For SN Types B and C, and BCR, BCP steels, the upper limit values for the yield strength is specified, and the YR has also to be less than 0.8 except for SN400A. These rules are proposed to ensure structures fail in an expected ductile mode as designed. The weldability is also considered by limiting the carbon content, equivalent carbon content, C_{eq} , carbon equivalent and composition parameter, P_{cm} . C_{eq} is widely employed to evaluate weldability of a steel, while P_{cm} is generally employed in Japan. The two variables are respectively given in Eqns. 1 and 2,

$$C_{eq} = C + \frac{Si}{24} + \frac{Mn}{6} + \frac{Ni}{40} + \frac{Cr}{5} + \frac{Mo}{4} + \frac{V}{14} \tag{1}$$

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \tag{2}$$

Table 1 Mechanical and Chemical Properties of SN Steels in Japan (JIS G 3136: 2012)

Steel grades	Yield strength (MPa)					Tensile strength (MPa)	Yield-to-tensile strength ratio					C_{eq} (Weight %)		Charpy impact energy at 0 ° (J)	
	6≤t≤12	12≤t<16	16	16<t≤40	40<t≤100		6≤t≤12	12≤t<16	16	16<t≤40	40<t≤100	t≤40	40<t≤100		
SN400A	≥235	≥235	≥235	≥235	≥215	400≤σ _t ≤510	-	-	-	-	-	-	-	-	≥27
SN400B	≥235	235≤σ _y ≤355	235≤σ _y ≤355	235≤σ _y ≤355	215≤σ _y ≤335		-	≤0.8	≤0.8	≤0.8	≤0.8	≤0.36	≤0.36		
SN400C	No product	No product	235<σ _y <355	235<σ _y <355	215<σ _y <335	No product	No product	≤0.8	≤0.8	≤0.8	≤0.36	≤0.36			
SN490B	≥325	325≤σ _y ≤445	325≤σ _y ≤445	325≤σ _y ≤445	295≤σ _y ≤415	-	≤0.8	≤0.8	≤0.8	≤0.8	≤0.44	≤0.46			
SN490C	No product	No product	325≤σ _y ≤445	325≤σ _y ≤445	295≤σ _y ≤415	490≤σ _t ≤610	No product	No product	≤0.8	≤0.8	≤0.44	≤0.46			

Charpy impact energy at 0 ° is required to be no less than 27 J for SN Types B and C, BCR and BCP steels, to improve their fracture-resistant properties. In addition, thickness direction properties

are also specified for Type C of SN and BCP steels. Applications of the SN, BCR and BCP steels in a welded steel frame (through diaphragm type) are shown in Figure 2 [21], where SN Type A steel is employed in secondary beams, SN Type B steel for beams and splice plates, SN Type C steel for diaphragms, BCR and BCP steels for columns. In Japan, the columns are commonly directly welded to the diaphragms, and the diaphragms are subjected to tensile stresses along the thickness direction under seismic loading. Thus, Type C steel is applied to the diaphragms.

2.2.2 High strength steels

High strength steels can reduce sectional size and thickness of structural members, which is correlated with reduced mass and gravity load. One of the main characteristics of high strength steels is a larger elastic domain compared with common mild steel. However, high strength steels are generally with a larger YR and a smaller elongation as illustrated in Figure 3, which are unfavorable for seismic design. For seismic design of structures, a small YR is favorable for a larger load-carrying capacity potential, and a large elongation is beneficial for its correlation with a large energy dissipation capacity. Therefore, application of high strength steels to seismic design of building structures is limited to only some structural components. On the other hand, a number of energy dissipation products have been proposed, and post-earthquake serviceability is paid more attention after the 1995 Kobe earthquake. A new design concept that main structural components such as beams and columns should remain elastic even during strong earthquakes receives more acknowledgements [7]. The seismic design concept for common steels and high strength ones are presented in Figure 4, where energy is dissipated through yielding of the beam and column ends for common steel frames, while through specific energy dissipation components for high strength steel frames. A research project aiming to develop a new damage-free structural system in intensity 7 earthquake (largest intensity in Japan) using super high strength steel has been carried out from the year of 2004 to 2008, e.g., [24-26]. To date, a number of super high strength steel grades, e.g., H-SA700 and BT-HT880, e.g., [27-29], have been proposed and recognized by the Japanese government. The mechanical and chemical properties of the high strength steels are listed in Table 2. It can be seen that the high strength steels have much larger C_{eq} and YR than SN steels, indicating poor weldability and ductility properties of the materials. The YR can reach as large as 0.98 [30]. Meanwhile, the V-notched Charpy impact energy requirements are much higher than those for SN steels, indicating favorable fracture-resistant properties.

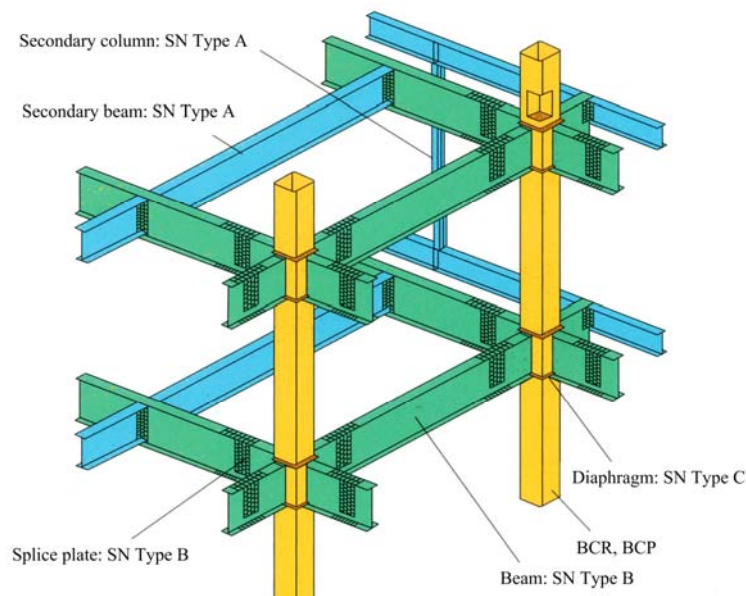


Figure 2 Application of SN and BCR, BCP Steels (adapted from [21])

Table 2 Steel Grades of High Strength Steels Qualified by Japanese Transportation Minister

Shape	Tensile Strength	Company	Grade	Size	C_{eq}	P_{cm}	Yield stress	YR	Charpy energy (J)	
Steel plate	780	Kobe JFE Nippon steel	H-SA700A	$6 \leq t \leq 50$	≤ 0.65	≤ 0.32	-	≤ 98	≥ 47	
			H-SA700B		≤ 0.60	≤ 0.30	-	≤ 98	≥ 47	
		Kobe	KBSA630B	$6 \leq t \leq 80$	-	≤ 0.30	630	≤ 85	≥ 47	
			KBSA630C	$16 \leq t \leq 80$	-	≤ 0.30	630	≤ 85	≥ 47	
		JFE	JFE-HITEN780TB	$22 \leq t \leq 100$	≤ 0.60	≤ 0.30	630	≤ 85	≥ 47	
			JFE-HITEN780TC	$22 \leq t \leq 100$	≤ 0.60	≤ 0.30	630	≤ 85	≥ 47	
			HBL630B-L	$12 \leq t \leq 40$	≤ 0.60	≤ 0.30	-	≤ 85	≥ 47	
			HBL630C-L	$12 \leq t \leq 40$	≤ 0.60	≤ 0.30	-	≤ 85	≥ 47	
		Nippon steel	BT-HT630B	$9 \leq t \leq 100$	≤ 0.60	≤ 0.30	630	≤ 85	≥ 47	
			BT-HT630C	$9 \leq t \leq 100$	≤ 0.62	≤ 0.30	630	≤ 85	≥ 47	
	950	Nippon steel	BT-HT880B BT-HT880C	$9 \leq t \leq 50$	≤ 0.60	≤ 0.34	810	≤ 98	≥ 70	
	Pipe	780	Nippon steel	SA-TT630	$\Phi 400 \sim 2200$	$19 \leq t \leq 60$	≤ 0.60	≤ 0.23	780	≤ 95
$60 \leq t \leq 80$					≤ 0.63	≤ 0.28				
Kobe			KAST630	$\Phi 400 \sim 2500$	$12 \leq t \leq 80$	-	≤ 0.30	780	≤ 90	≥ 47

Note: YR denotes yield-to-tensile strength ratio

To date, there are several applications of high strength steels to building structures. For example, concrete filled high strength steel columns (780 MPa steel) are employed in Obayashi Corporation’s Technical Research Institute Main Building “Techno-Station” as illustrated in Figure 5 [31], where 160 MPa high strength concrete is adopted. The slender columns have a superior architectural effect, and large span and space is realized by the application of the high strength steel. Amagasaki Research and Development Center shown in Figure 6 [32] is the first application of the 1000 MPa high strength steel in the world, and the high strength steels are employed in columns of the first floor, where buckling restrained braces (BRBs) are also employed to absorb seismic energy during a strong earthquake. Sliding column bases and shear panels with the details shown in Figure 7 [32] are employed to prevent the beams and columns from yielding, and the beams and columns are designed to remain elastic even during a strong earthquake.

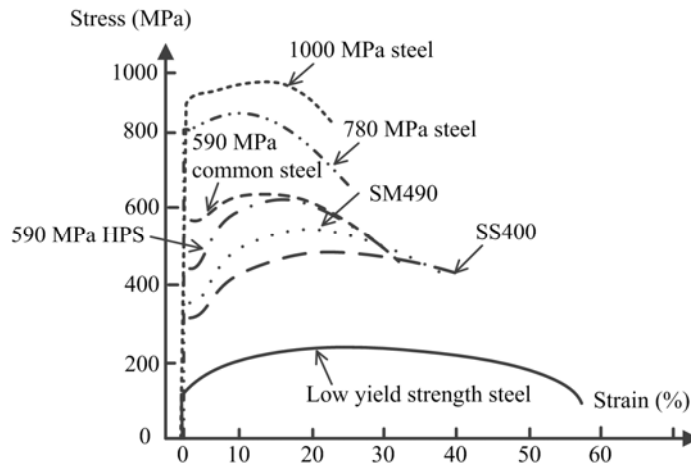


Figure 3. Stress-strain Curves of Common and High Performance Steels

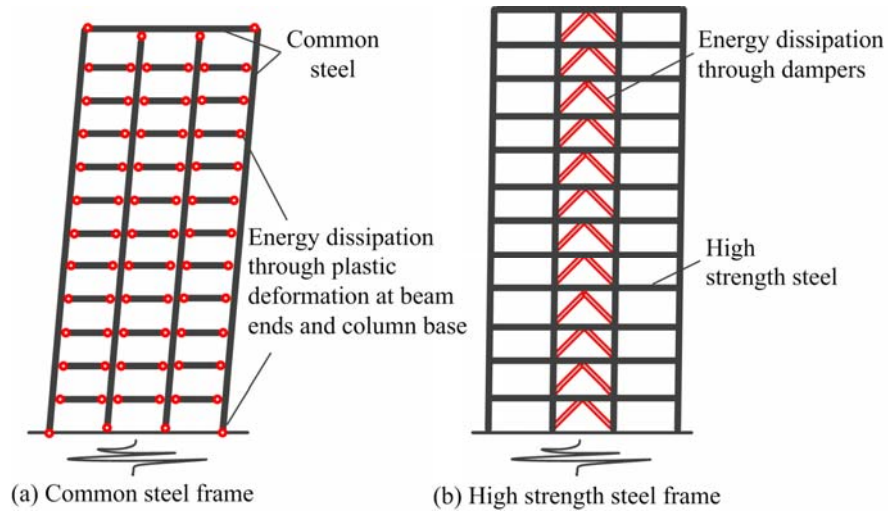


Figure 4. Seismic Design Concept for Framed Structures Made of Common Steel and High Strength Steel



Figure 5. Application of 780 MPa High Strength Steel (adapted from [31])

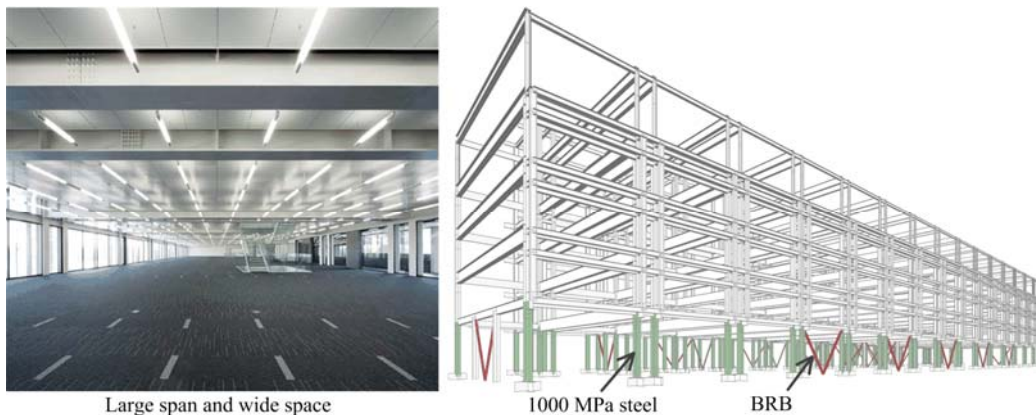


Figure 6. Application of 1000 MPa High Strength Steel (adapted from [32])

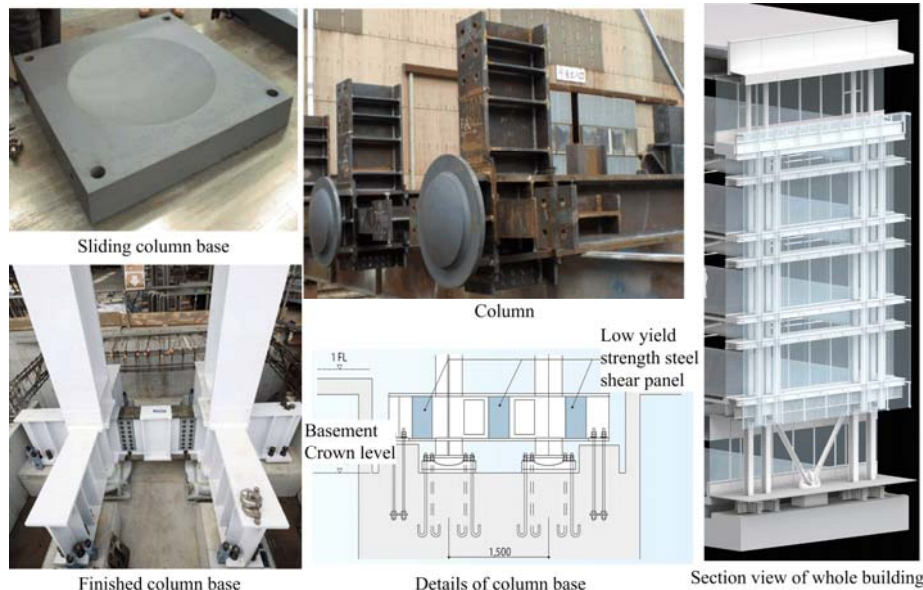


Figure 7. Details of Column Base in a Building Made of 1000 MPa High Strength Steel (adapted from [32])

2.3 Ductility Related HPSs

In recent several decades, a number of energy dissipation components, e.g., BRBs, oil dampers and shear fuses, have been developed and prevalently applied to seismic design of both building and bridge structures, where metallic dampers dissipating energy through plastic deforming of materials are a main category. Energy dissipation capacities of this type of dampers are mainly dependent on ductility of the material. A series of low-yield strength steels are developed aiming to improve the energy dissipation capacities of metallic dampers. In the year of 2000, low yield strength steels LY100 and LY225 for application to building structures were recognized by the Japanese government. The main characteristics of the two steels are:

- (1) strict control for the yield strength ranges (LY100: 80-120 MPa; LY225: 200-245 MPa);
- (2) high ductility in terms of elongation (LY100: $\geq 50\%$; LY225: $\geq 40\%$).

The ductility of the low strength steels is approximately twice of a common structural steel with an elongation of 20%. Meanwhile, the YRs for LY100 and LY225 are also respectively restrained to be less than 0.6 and 0.8. Some dampers such as BRBs have relatively large load-carrying capacities, which may induce premature failure of the attached connections and frames. The low yield strength steels have a tensile capacity one third to half of common steels, which can thus greatly reduce the demanding load-carrying capacities of the attached structural components.

2.4 Fireproofing HPS

Fire resistant property is one of the main concerns in steel structures, and commonly fireproofing coating is required to prevent sudden loss of load-carrying capacity of steel structural components. However, it takes time and expense to carry out fireproofing coating, and it also impairs architectural values of structures. To overcome these deficiencies, fireproofing steel is developed to shorten construction period, enlarge effective architectural space and reduce costs of maintenance etc. The steel has equivalent mechanical properties with common structural steel under normal temperature, while lower decreasing rate of load-carrying capacity compared with common steel under high temperature as shown in Figure 8 [33]. The fireproofing steel SN490-FR under 600 °C

can sustain more than two thirds of the yield strength under normal temperature. It has been employed in parking lots, atriums, external steel structures, art galleries, gyms etc., and an application to external steel structure is illustrated in Figure 9 [33].

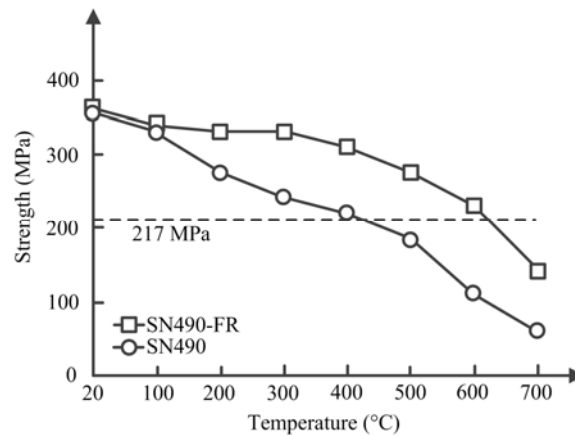


Figure 8. Comparison of Fireproofing Steel and Common Steel (adapted from [33])



Figure 9. Application of Fireproofing Steel in a Building Structure (adapted from [33])

3. HIGH PERFORMANCE STEELS IN BRIDGE STRUCTURES

3.1 General Comments

Vehicle dynamic load make fatigue cracking a main issue in steel bridges, which is different from steel buildings. Meanwhile, steel bridges are frequently exposed to more corrosive environments, and this corrosion is significantly enhanced due to marine (salt spray) exposures especially in Japan. Another issue is that many aging bridges constructed over 50 years ago require maintenance or rehabilitation. Design concept based on LCC [1] is increasing popular in new constructed and rehabilitated steel bridges, along with the aforementioned characteristics make durability related properties of steel more demanding in bridge structures.

The application history of steel to bridges along with the revisions of specifications for highway bridges is presented in Figure 10 [6], which indicates that weathering steels have been employed for a long history since around the year of 1973. A significant progress in manufacturing technology is the thermo-mechanical control process (TMCP) initiating in 1980s. Fine microstructures produced using the controlled-rolling and controlled-cooling method as shown in Figure 11 [34] can greatly improve the strength and toughness properties of steel. Main

advancement of HPSs in bridge structures occurred in 1990s, and a large variety of HPSs have been developed using the TMCP technology and employed in practice based on the revised specification.

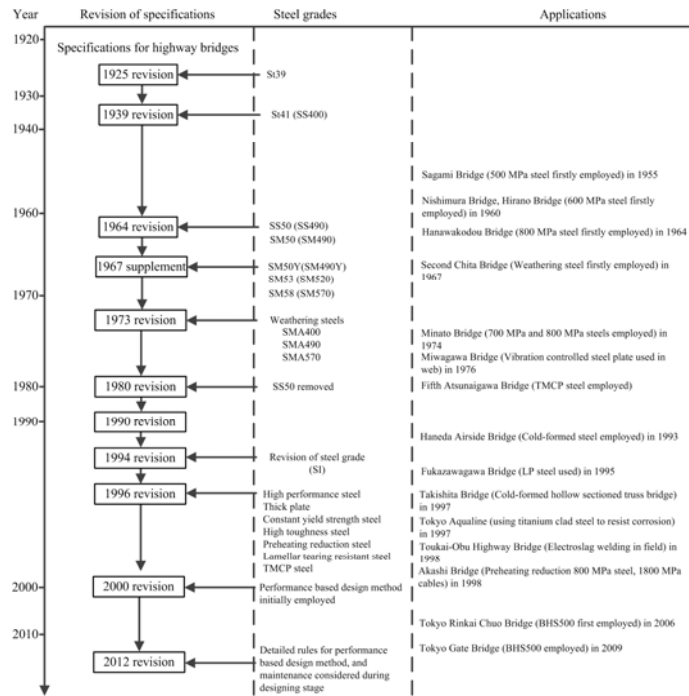


Figure 10. History of High Performance Steel in Steel Bridges (adapted from [6])

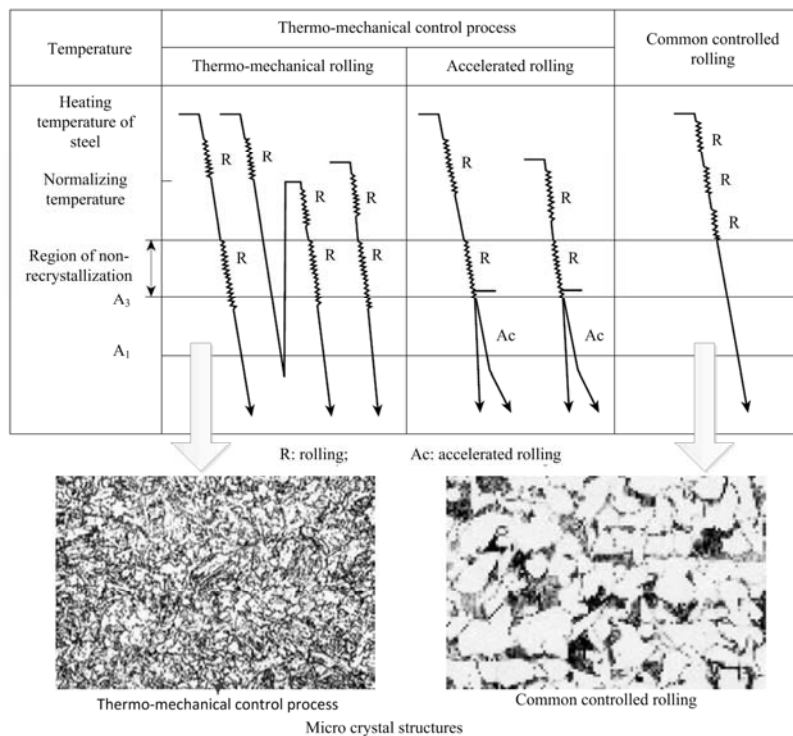


Figure 11. Thermo-mechanical Control Process for Plate Rolling (JIS G0201)

3.2 Strength Related HPS

3.2.1 Constant yield strength steels

Yield strength of common steel generally decreases as plate thickness increases. For example, yield strength decreases when plate thickness is over 40 mm for most Japanese structural steels. A new series of constant yield strength steels listed in Table 3 for plate thickness within 40-100 mm are developed. Yield strength versus plate thickness curve of a constant yield strength steel, SM520-H [35], is compared with a common steel, SM520, in Figure 12. The constant yield strength steels have the following two virtues:

- (1) constant yield strength for various plate thickness makes design simpler;
- (2) yield strength of a thick plate is increased, which can reduce self-weight and makes design more economical.

3.2.2 High strength cables

Suspension bridge and cable stayed bridge are two popular structural types for long span bridges. In recent decades, strength of the cables is increasing gradually as illustrated in Figure 13. The high strength cables have the following merits:

Table 3 Yield strength of constant yield strengths steel and common steels

Constant yield strength steel	Plate thickness (mm)	SM400C-H SMA400CW-H	SM490C-H	SM520C-H SMA490CW-H	SM570-H SM570W-H
		40 < t ≤ 100	140	185	210
Common JIS steel	Plate thickness (mm)	SM400 SMA400W	SM490	SM520 SMA490W	SM570 SM570W
	16 < t ≤ 40	140	185	210	255
	40 < t ≤ 75	125	175	195	245
	75 < t ≤ 100	125	175	190	240

- (1) reduce self-weight of the slabs;
- (2) reduce self-weight of other structural components;
- (3) more feasibility in structural design;
- (4) shorten construction period and reduce cost of a whole project.

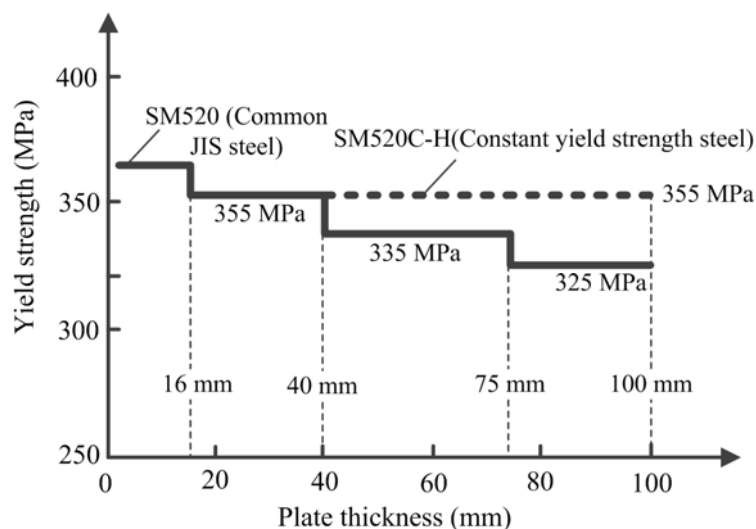


Figure 12. Yield Strength of Constant Strength Steel and Common Steel

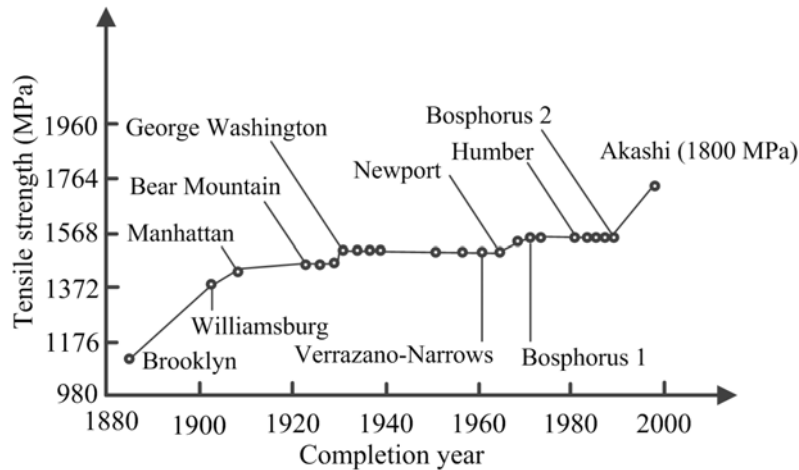


Figure 13. Development of High Strength Cables in Bridges

The strength of the two main cables employed in the Akashi bridge can reach 1800 MPa. It is reported that four main cables are required if 1600 MPa cables are employed. Not only the self-weight of the cables, but also the self-weight of the main towers and the bridge deck is reduced by approximately 10%. Meanwhile, the height of the main towers is also reduced from 320 m to 283 m for the increase of the cable strength.

3.3 Toughness Related HPS

Several properties are correlated with toughness of structural steel, such as cold forming properties and brittle fracture-resistant properties under low temperatures. It is known that cold forming will greatly reduce the ductility and toughness at regions with large bending curvatures (small bending radii). A material can fracture even during cold forming if the toughness is too low or the bending radius is too small. For common structural steel, a large bending radius of 15 times of the plate thickness is required. A series of high toughness steels are developed, and the bending radius can be reduced to 5 or 7 times of the plate thickness depending on the toughness of the material as shown in Figure 14 [35]. Besides, in cold areas such as Hokkaido in Japan, the temperature can decrease as low as $-40\text{ }^{\circ}\text{C}$, and high toughness steels are required to resist brittle fracture under the low temperature and meanwhile maintain ductility under a strong earthquake.

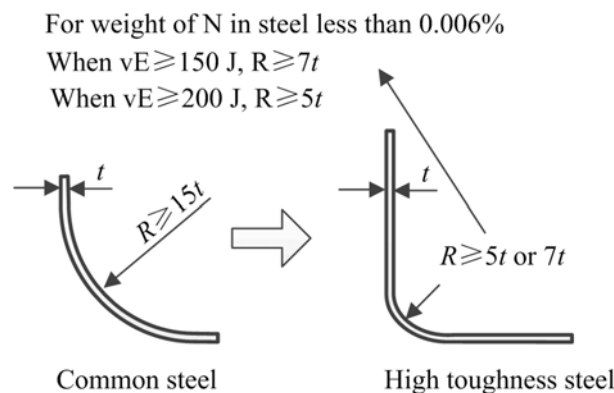


Figure 14. Favorable Cold Forming Properties of High Toughness Steel

3.4 Weldability Related HPS

3.4.1 Steel for high heat input welding

Generally, tungsten inert gas (TIG) welding, metal inert gas (MIG) welding and electro-slag welding (ESW) are widely employed in bridge engineering. For common structural steel, a large amount of heat input will induce low toughness at the heat affected zone, and premature brittle fracture may occur. Therefore, strict control of the heat input is required in some design specifications, e.g., the maximum heat input for SM570 and SM490 are respective 70 J and 100 J in Japan [35]. On the other hand, welding using high heat input method such as the single pass welding process, ESW, is more productive compared with the multi-pass welding methods such as TIG and MIG, while the heat input is generally more than 370 J, which is more than the specified value of the design code. A series of steel for high heat input welding is thus developed. Besides the high efficiency, the steel can also reduce the construction cost, especially for thick-walled steel plates. The welded connections using the steel also have high Charpy impact energy compared with common steel as illustrated in Figure 15. The micro-structure of the heat-affected zone using the steel for high heat input is much finer than those using conventional steel, and the weld thus has a superior fracture-resistant capacity. The micro-structure of a welded joint using the ESW process is shown in Figure 16 [36].

3.4.2 Reduced preheating steel

Weldability is commonly evaluated by the P_{cm} in Japan, and a large value of P_{cm} is correlated with poor weldability. Therefore, weldability becomes poor as the alloy content increases, and a thick-walled plate also has poor weldability. To avoid welding cracks, preheating is commonly required for thick-walled steel plates, especially in steel bridges where thick-walled plates are widely employed. However, it is not only inefficient but also difficult to carry out high temperature preheating in practice. A series of steel is developed to lower the required preheating temperature, and the steel has a relatively small value of P_{cm} as shown in Figure 17, where the required preheating temperature can be controlled within 50 °C.

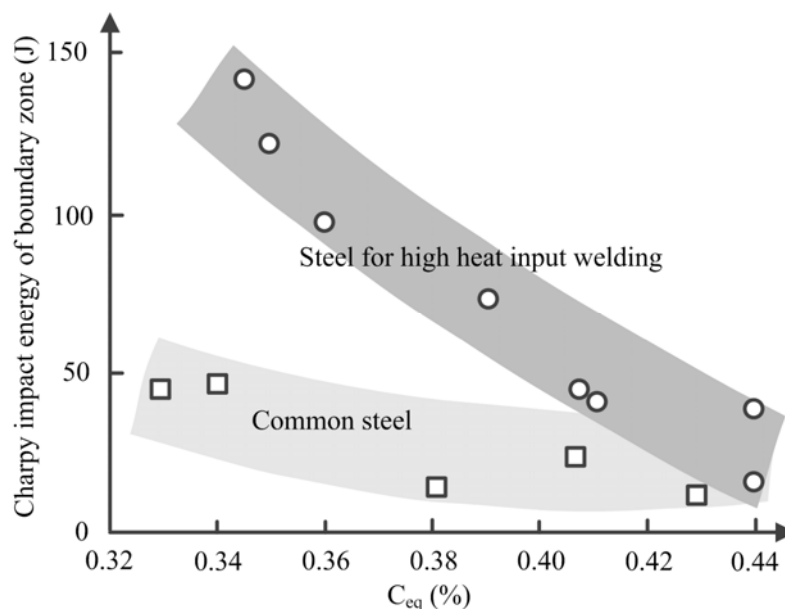


Figure 15. Comparison of toughness at Boundary Zone between Steel for High Heat Input Welding and Common Steel

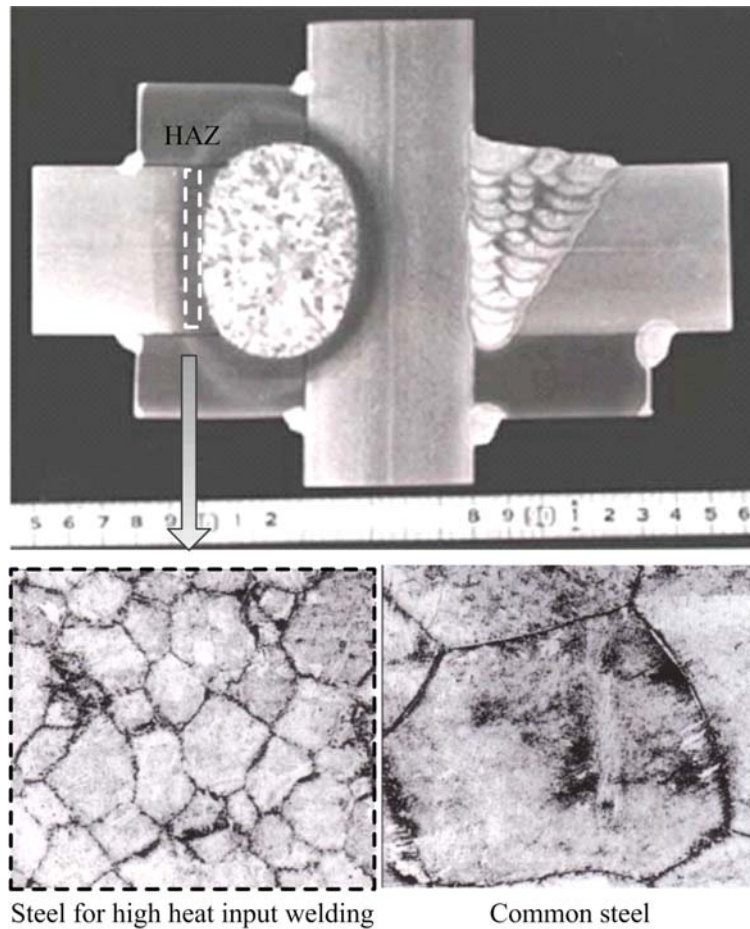


Figure 16. Application of Steel for High Heat Input Welding (adapted from [36])

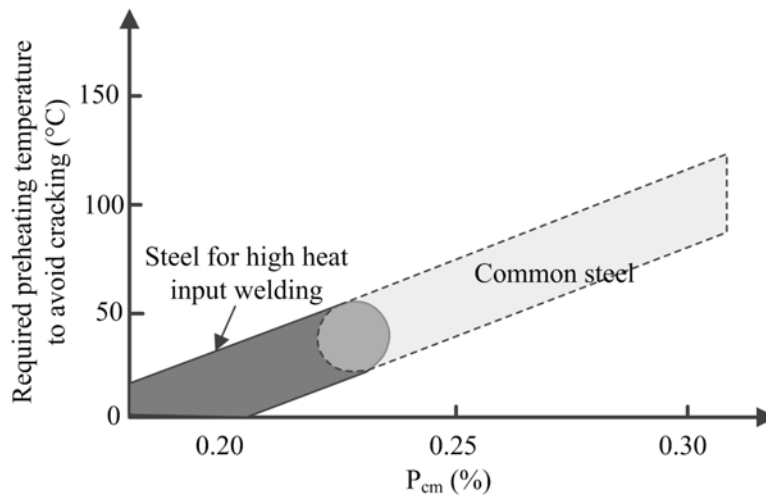


Figure 17 Preheating Requirements of Common Steel and Steel for High Heat Input Welding

3.4.3 Lamellar tearing-resistant steel

Impurities tend to accumulate at mid-thickness of a steel plate, and a thick-walled steel plate subjected to tensile stress along the thickness direction is susceptible to lamellar tearing as

illustrated in Figure 18. The main affecting impurity for lamellar tearing is MnS. A series of lamellar tearing-resistant steel is developed by limiting the S content within 0.006% to 0.01%, which corresponds to a reduction of area at fracture along the thickness direction within 15% to 35% [37]. The steel is applicable to welded thick-walled steel joints such as column flanges of beam-column connections.

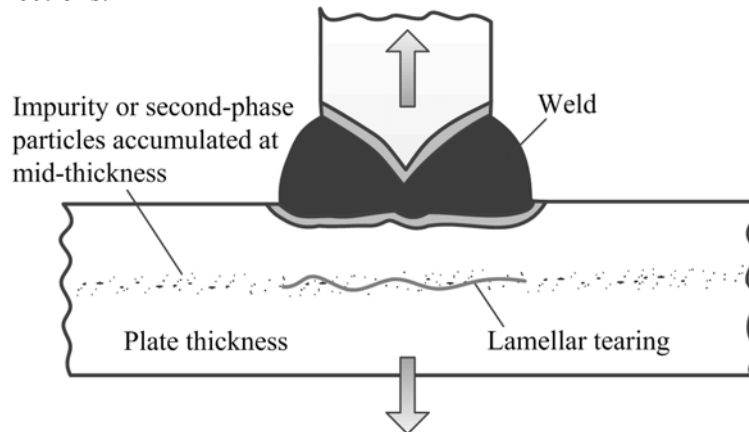
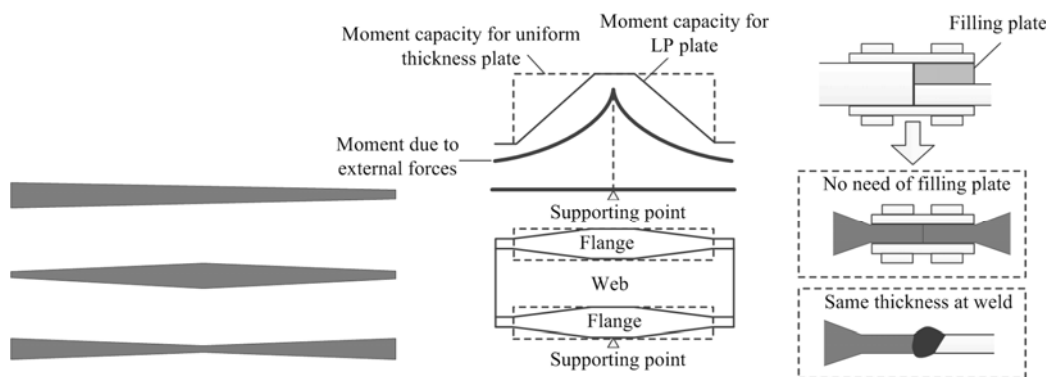


Figure 18. Illustration of Lamellar Tearing at Thick Steel Plates

3.5 Connection Feasibility Related HPS

Longitudinally profiled (LP) steel plates as shown in Figure 19 is another series of HPS developed for steel bridges. The LP steel plates have tapered sections along the thickness direction, which makes connections between two plates with different thickness simple. The stress conditions within the LP steel plates are also improved for the changing plate thickness. For these two virtues, less manufacturing work is required to connect two steel plates with different thickness, and the self-weight is also greatly reduced compared with common steel plates, which thus lower the construction fee.



(a) Profile along longitudinal direction (b) More economical solutions at supporting point and joints

Figure 19. Longitudinally Profiled Steel Plates and its Applications

3.6 Durability Related HPS

Weathering properties are very important for steel bridges, where commonly painting is required to protect the bridges from corrosion. Weathering steels are developed to enhance the corrosion-resistant properties of steel bridges, which have equivalent mechanical properties with common structural steel. These steels are commonly low alloy steels containing chemicals such as Cu, Cr and Ni etc. The steels will form a fine rust layer in the presence of moisture and air as

illustrated in Figure 20, which will prevent the inner material from further corrosion. For this mechanism, the rusting rate will be greatly slowed down compared with conventional steel. There are several benefits for application of the weathering steels, such as rapid construction, attractive appearance, minimal maintenance, and flexibility in future use. The steel bridges using weathering steels are more economical from the viewpoint of LCC.

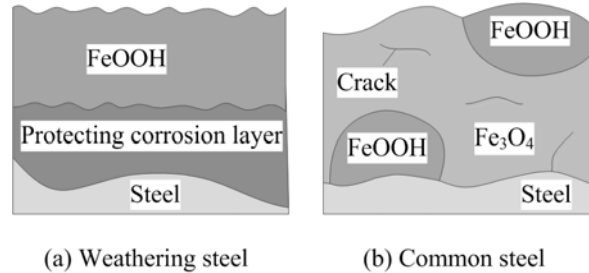


Figure 20. Illustration of Corrosion Mechanisms for Weathering Steel and Common Steel

3.7 New HPSs for Steel Bridges

A series of new HPSs termed BHS (bridge high performance steel) [38] have been developed to reduce the construction and maintenance costs of steel bridges. There are two steel grades, BHS500 and BHS700 (the current names are respective SBHS500 and SBHS700) [39], respectively with yield strengths no less than 500 MPa and 700 MPa. The main characteristics of the BHS include:

- (1) high yield strength;
- (2) favorable construction feasibility such as large welding heat input as much as 10 kJ/mm and reduced preheating temperature as listed in Table 4;
- (3) high toughness;
- (4) good weathering properties such as BHS500W and BHS700W, where “W” denotes weathering.

The BHS has been firstly employed in the construction of Tokyo Rinkai Chuo bridge in 2006, where most of the members in the truss bridge uses the new steel as shown in Figure 21 [40]. It is reported that the self-weight and manufacturing cost have been respectively reduced by approximately 3% and 12%.

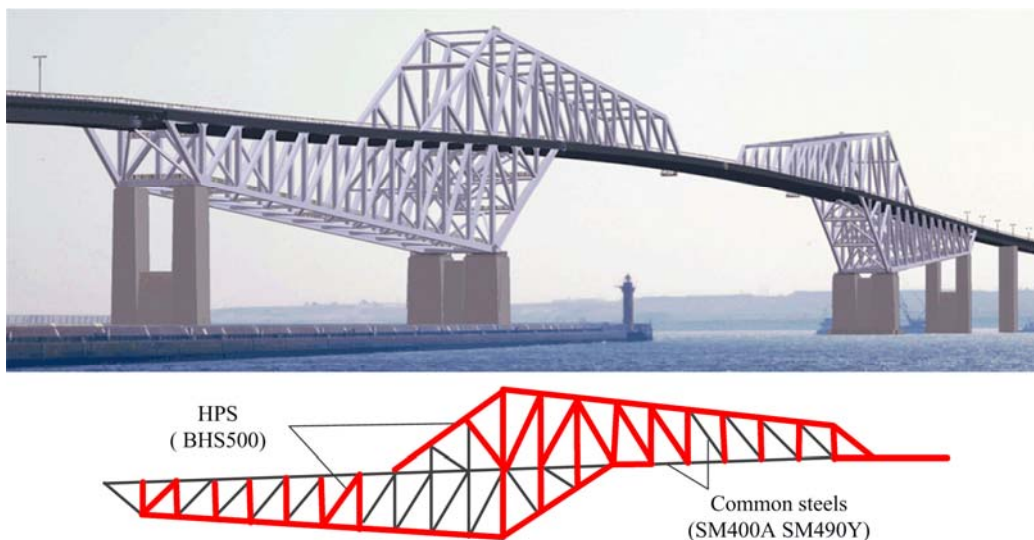


Figure 21. Application of High Performance Steel in Tokyo Rinkai Chuo Bridge (adapted from [40])

Table 4. Preheating Requirements for BHS Steels and Common Steels

Strength (MPa)	Type	Classification	Thickness			
			t≤25	25<t≤40	40<t≤50	50<t≤100
570	SM570	Standard P _{cm}	0.26 (no preheating)	0.27 (80°)		0.27 (100°)
		No need to preheating P _{cm}	-	0.24	0.22	
	BHS500	P _{cm}	≤0.20 (no need to preheating)			
	BHS500W	P _{cm}	≤0.20 (no need to preheating)			
780	HT80		t≤25	25<t≤38	38<t≤50	50<t≤75
		Standard temp. (°)	100	100	100	120
	BHS700W	Min. preheating temp. (°)	50			

4. SOCIAL AND ACADEMIC IMPACTS OF HPSS

A number of high performance steels (HPSs) in Japan have been discussed in this study. These steels have great impacts on the whole society, such as:

- (1) low construction and maintenance costs for steel structures;
- (2) safer structures for the improved mechanical properties such as more stable yield strength and higher toughness;
- (3) rapid construction speed;
- (4) more feasibility for challenging structural proposals, e.g., high strength steel makes larger scaled structures possible.

There are also significant impacts on academic research of structural engineering, such as:

- (1) new design methods for structures made of HPS;
- (2) innovative structural systems;
- (3) new energy dissipation components;
- (4) new connecting technologies.

More research efforts are still required to promote the developments of these new technologies, and there is great potential for the application of HPS in future.

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