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Creation of high quality and cost-effective bridges using newly developed steels for bridge high-performance structures (SBHS)

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ABSTRACT: This article describes how advanced steels have contributed to the construction of high-quality, economical bridges. Analogous to the development process of modern states, the development process of bridge technology is classified into the following three stages: (1) the period of establishing bridge construction technology; (2) the period of the mass production of bridges; and (3) the period of maintaining bridges. In every stage, the highest emphasis has been put on building bridges with safety, high durability, and high cost efficiency for their entire operation period. This article describes the history of the steel bridge construction in Japan and then presents a new type of high-performance steel that has recently been developed.

1 INTRODUCTION

Infrastructure construction plays a great role in developing society and economy. Especially, bridges are important structures that can serve as local landmarks. The advancement of the construction technology has a great impact on society. In the case of steel bridges, the performance improvement of steel as the base material directly leads to the further sophisticated design, production, and construction technologies. The improved steels largely contribute to the performance improvement of the final structures.

This article describes the development history of steel bridges in Japan as well as the role of steels. This paper also presents high-performance steels developed in response to recent requirements originating from society and foresees further performance improvement of steel bridges using the high-performance steel materials.

2 THE DEVELOPMENT OF STEEL BRIDGES IN JAPAN (JBA, 2004)

2.1 *First Period: From the Stage of Importing Bridges to the Initial Stage of Domestic Production*

The history of iron bridges in Japan began with the bridges constructed in port towns with foreign settlements as a symbol of westernization that started around 1870, when the modern period started. In 1868, the first iron bridge, Kurogane Bridge, was built in Nagasaki. It was followed by Yoshida Bridge, built in Yokohama in the next year. Both bridges had a length of over 20 meters. The former bridge was a girder bridge designed by a Dutch engineer; the latter bridge was a truss bridge designed by a British engineer. Wrought iron was imported as the base material to manufacture the bridges in Japanese factories. Approximately ninety years had passed since the world’s first iron bridge appeared in England.

In the 1870s, the development of railroads and highways started, supported by the technology import from the Western countries. In this initial period, bridges were built with technological support from European and American engineers. The support ranged from the design to production and construction processes. In that period, the construction of railroad networks was especially prioritized. All railroad bridges were imported from the countries corresponding to the nationalities of the engineers who coached the railroad construction, such as England, Germany, and the US. Either cast iron or wrought iron was used for the bridges. Some of the imported iron bridges still remain and can be found. Photo 1 shows some examples. They have actually been used for over one hundred years, although their present purposes are different from the original ones.

Supported by the Japanese government, an engineer education system was developed in the early years to realize the domestic production of bridges. As a result, all bridges began to be produced domestically about the end of the Meiji Era (1912).

(a) Ryokuchi Nishi Bridge (made in Germany, 1873) (b) Hama-Nakatsu Bridge (made in England, 1874)

Photo 1. Old Steel Bridges imported from foreign countries

Photo 2. Eitai bridge

Photo 3. Minami Kawachi bridge

Meanwhile, the type of iron used for bridges changed from cast iron or wrought iron to steel. Japan had almost depended on imported iron materials until the end of the nineteenth century. In 1901, however, Yawata Steel Works started its operation as a Japanese modern steelworks. Since then, Japan had gradually decreased the amount of steel imports, and the country became almost self-sufficient in steel by around 1925.

The Japanese bridge technology intensively developed, driven by the disaster reconstruction project after the Great Kanto Earthquake, which struck Japan in 1923. Various steel bridges were built before around 1940, when World War II started. Photo 2 shows Eitai Bridge, a representative example of the bridges built through the earthquake disaster reconstruction project. Eitai Bridge was the first bridge among the nine "earthquake disaster reconstruction bridges" built over the Sumidagawa River in Tokyo. Young Japanese engineers, including Enzo Ohta and Yutaka Tanaka, designed each bridge using the then-cutting-edge bridge technologies. The bridges have been Tokyo's major symbols for ninety years since their construction. For the tie member tying Eitai Bridge's arch ends to each other, a high-tensile manganese steel (Ducol steel), which was being developed by the Navy, was used. The wise decision of the bridge engineers are admirable because the high-tensile steel used is the one that is still classified as a high-strength steel.

The construction process of Minami-Kawachi Bridge (Photo.3) also represents the Japanese bridge technology at that time. The bridge was one of a series of great structures constructed by Yawata Steel Works to meet the rapid increasing demand for steel after World War I. The bridge was a lenticular truss bridge in which steel members were combined in a lens form. While over 300 bridges of this type were built in the US, only three were built in Japan. Minami-Kawachi Bridge is the only bridge that still exists in this rare form. The construction of the Kawachi water reservoir was a great work, designed and administered by the engineers of the Works lead by Hisanori Numata. The construction took eight years, during which no worker was killed. The civil engineers of the Works used the steel material produced in-house to complete the huge project independently without support from foreign engineers.

Thus, at the beginning, Japanese steel bridges were built with technological support from skilled foreign engineers. Then, Japanese engineers learned and accumulated the technologies during construction works and finally established the stand-alone technology for domestic production.

2.2 *Second Period: the Period of Bridge Mass Production Driven by High-Speed Traffic Networks Construction*

Bridge construction stagnated during World War II, but began to advance again, driven by the overall economic and social rehabilitation, in the 1950s, when Japan broke from the chaos caused by the war.

It was followed by the rapid economic growth period, when high-speed railroads and expressways connecting cities nationwide as well as urban expressways were planned and constructed. Traffic networks were developed at a feverish pace to make a success of national events such as the 1964 Summer Olympics in Tokyo and the 1970 Japan World Exposition in Osaka. A standardized structure design was established to enable mass construction at a faster pace under different constraints. Many steel structures were built by utilizing the characteristics of steel.

Subsequently, as Japan’s economic power was expanding, the need to build bridges crossing the sea increased. The period of building huge bridges came, requiring high technologies to aim for the world’s top player.

The following subsections give representative examples of these bridge construction projects: Metropolitan Expressway; Tokaido-Shinkansen (Bullet Train) Line; and the Honshu-Shikoku Bridges.

2.2.1 *Metropolitan expressway*

Tokyo’s traffic became increasingly heavy after 1950, as the economy was recovering. The city roads were predicted to be paralyzed around 1965. In order to improve this situation, the Metropolitan Expressway was planned to be constructed as “highways with continuous grade separations” to complement the road function of the metropolitan area.

The Metropolitan Expressway was initially planned as an automobile expressway network with a total length of 71 km including a ring road surrounding the metropolitan area and eight radial roads. After Tokyo was selected to host the Olympics in 1959, the construction of approximately 32 km of the roads was highly prioritized as Olympics-related roads to connect the related facilities with the airport.

It was constructed by making full use of the lands owned by national and local governments including main roads and the ship channels that had been used since the Edo Era(1603-1868). Photo.4 shows an example view of the present Metropolitan Expressway. As shown, it has a complex three-dimensional structure to make effective use of the city space. The characteristics of steel were used to realize the structure under various constrains such as a severely limited usable space, construction works in such a small space, and the reduction of the construction period.

Photo 4. Metropolitan Expressway

2.2.2 *Tokaido-Shinkansen (Bullet Train) Line (JNR, 1965)*

The demand for railroad transportation also rapidly increased owing to the reconstruction. Therefore, the capacity of main lines, which had been seriously damaged during World War II, reached their limits. The Shinkansen Project was born against this background. The project aimed to build a high-speed railroad operating approximately 500km between Tokyo and Osaka, Japan’s two biggest cities, at a maximum speed of 200 km/h in approximately three hours. As the railroad industry was declining at that time in the world, the construction of the new high-speed railroad requiring a huge investment was the target of criticism from the mass media. Strong objections were raised even from inside the Japan National Railways (JNR), which was the body responsible for the construction. In 1958, however, the construction project was approved with support from Shinji Sogo, President of JNR, and other executives who had strong determination. In 1964, only six years after the start of the construction, the bullet train line was launched just before the opening of the Tokyo Olympic Games.

The railroad line was built by making maximum use of the technologies accumulated until then and based on the 3S design policy (standardizing, simplifying, and smart thinking). Table 1 shows the numbers of steel bridges built for Tokaido-Shinkansen by girder type. The standard for girders was designed as follows: the truss type for bridges with a length of over 50 meters, the box-type plate girder for 30–50 meters, and the plate girder or a unified type for 20–35 meters, except for some special structures. Full shop welding and high-strength bolts for on-site jointing were adopted. Such standardization and adoption of new technologies remarkably reduced the construction period.

Photo 5. Truss bridge of Shinkansen

Table.1 The number of the girders of steel bridges built for Tokaido-Shinkansen Line(518 km)

Girder type	Deck girder			Through girder	Truss	Composite girder	Total
	I-section girder	Box-girder	Subtotal				
Number (Spans)	194	139	333	155	135	258	881

2.2.3 *The Honshu-Shikoku Bridges*

A number of large bridges have been built over straits in Japan, which consists of many islands of various sizes. In 1970, Honshu-Shikoku Bridge Authority was founded according to the decision to construct three routes connecting Honshu Island and Shikoku Island over the Seto Inland Sea. These routes were planned to cross the Sea with a distance of over ten kilometers hopping from island to island. In this project, many huge bridges were built with a wide variety of types such as suspension, cable-stayed, arch, and truss bridges, which led to the further development of bride construction technologies.

With its world’s longest central span (1,991 m), Akashi Kaikyo Bridge is a leading example of the Honshu-Shikoku Bridges. The construction was completed in 1998. Some newly developed materials were applied to the bridge, including galvanized steel wires with a strength of over 1,770 MPa, 200 MPa higher than the strength of the previous steels, and the reduced preheating type high-strength steel HT780 with a tensile strength of over 780 N/mm^2, which could reduce the minimum preheating temperature for welding from 100ºC to 50ºC. These new materials reduced the total weight and labor for production, contributing considerably to reducing the cost of construction of the bridge with the world’s longest span.

Photo 6. Akashi Kaikyo bridge

In the period when bridges were mass-produced and huge bridges were built with the aim for the world’s top player, performance improvements such as strengthening steels and enhancing productivity significantly contributed to the rapid development of traffic networks and the construction of huge bridges.

2.3 *Third Period: The Period of Building Low-Cost Bridges with High Durability*

Figure.1 shows the trends of the number of highway bridges by construction year. The number of the bridge construction largely increased from around 1960, when the rapid economic growth started. From now on, a large number of bridges built in the period of the rapid economic growth will be aging, and the number of bridges aged 50 years or older will rapidly increase. Recently, an increased number of bridge failures caused by aging has been reported. The increasing costs required for maintenance and replacement has become a serious problem. In the period when bridges were mass-produced, cost efficiency in the initial investment was prioritized; hence, reducing the initial construction cost was required. However, nowadays an increasing number of bridges have been constructed while existing bridges are aging. Therefore, the attention is directed to the minimization of the life cycle cost (LCC) by considering not only the maintenance and management cost but also the future cost for replacement. To minimize the LCC, it is required to build a new structure by simultaneously maximizing the life-span and minimizing investments including the initial investment as well as the costs for maintenance, repair and reinforcing works required in future.

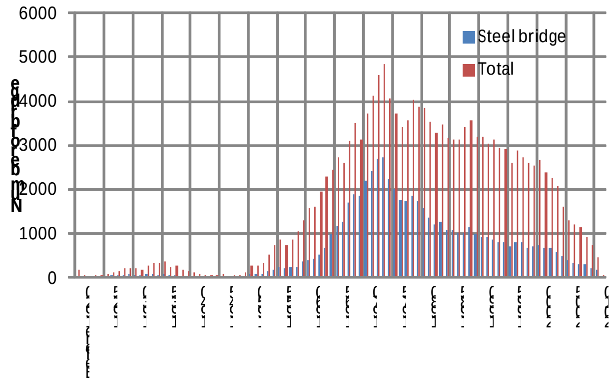

Figure 1. The number of highway bridges by construction year (NILIM,2015)

Recently, it is essential in the construction of steel bridges to respond to diverse social requirements, such as reducing construction costs, improving durability, and increasing reliability. Improvement in the performance of steels significantly contributes to enhancing the functions of steel bridges. It is possible to meet various requirements by developing and using high-performance steels.

In the next chapter, SBHS, a high-performance steel that has been recently developed in Japan, is described.

3 HIGH-PERFORMANCE STEEL PLATES FOR BRIDGES (SBHS:STEELS FOR BRIDGE HIGH PERFORMANCE STRUCTURE)

In order to satisfy the performance requirements for bridge construction, SBHS was developed to establish a material standard that can benefit the design and production of bridges(JSA,2011). The thermo-mechanical control process (TMCP), a leading-edge technology reflecting the advancement of Japan's steel production technology, was applied to obtain high strength, toughness and weldability with crystal grain refining. The development of SBHS also aimed to improve material's mechanical properties and various characteristics relating to quality to obtain superior characteristics suitable for the design and production processes as well as the quality, safety, and durability of steel bridges. Some analyses conducted in trial design and actual bridges revealed that the steels with a yield strength of 500 N/mm^2 or under minimize the cost of bridges with short to medium spans by reducing the steel weight (Homma,et.al.,1995). For huge bridges with a span of 500 meters or longer, the reduction of the dead load by decreasing the deadweight contributes to increasing cost efficiency. Thus, in the case of these bridges, it is economical to use the steels with a yield point of 700 N/mm^2 or higher. In the following sections, the characteristics and expected effects of SBHS are described.

3.1 *High Strength*

As shown in the Figure.2, the SBHS grades have yield strengths (400, 500, 700 N/mm^2) higher than those of the conventional JIS steels (355 N/mm^2 for SM490Y, 450 N/mm^2 for SM570, and 685 N/mm^2 for HT780 in plates with a standard thickness of 16–40 mm). The effective design of the cross-section of the bridge components and the reduction of the total steel weight can be realized by utilizing SBHS's high yield strength.

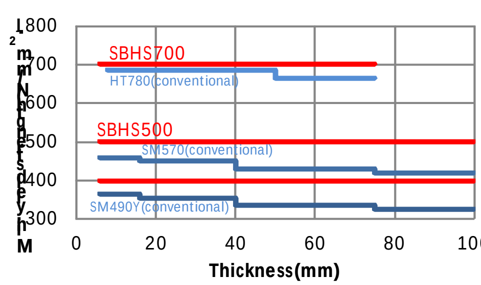

Figure 2. Yield strength of SBHS

Table.2 Preheating temperature and maximum heat input

Steel Grade	Thickness of plate (mm)	Weld crack sensitive parameter, P_{CM}	Preheating temperature	Maximum heat input (kJ/mm)
SBHS400	$6 \leqq t \leqq 100$	$\leqq 0.22$	No need	10
SBHS500	$6 \leqq t \leqq 100$	$\leqq 0.20$	No need	10
SBHS700	$6 \leqq t \leqq 50$	$\leqq 0.30$	50℃	5
	$50 < t \leqq 75$	$\leqq 0.32$		

3.2 *Good Weldability*

High-strength steels of the grade SM570 or higher generally have weldability inferior to that of the commonly used SM490Y. Therefore, some limitations are usually applied to the preheating process, heat input, and interpass temperature in welding. The upgraded weldability of the SBHS enhances the welding efficiency through bypassing the preheating process or reducing the temperature (Table.2).

In Tokyo Gate Bridge, the improved weldability of SBHS was fully utilized to increase work efficiency. For example, preheating at truss joints (See Photo.7) was removed from the on-site welding process. The conventional high-strength steels required the preheating process to prevent the cold cracking, which formed a cause of productivity decline. SBHS can reduce or omit the preheating workloads by holding down its weld crack sensitivity index (P_{CM}), which provides indications for the need of preheating and preheating temperature, to achieve high strength and good weldability at the same time(Homma,et.al.,2015).

Photo 7. Field welding of SBHS

Photo 8. Nagata bridge

3.3 *Good Formability*

The cold bending processing of steels is a useful method to produce steel bridges. It is used for various components such as main girders, towers, piers, slabs, and tubes. The cold bending processing of steels, however, requires sufficient consideration on the embrittlement caused by the strain aging. In the Japanese specifications for highway bridges(JRA,2012), a certain limit is defined for the cold bending processing radius (R; normally $R \geq 15t$).

To realize more flexible design, the SBHS specification was defined to adapt to the cold bending processing with a small processing radius by achieving the special quality standard value of the Charpy absorption energy corresponding to the practical minimum radius ($R = 5t$)(Homma,et.al.,1997). For example, the energy is 200 J at –5ºC for the SBHS500 grade. SBHS500 enabled to produce extremely thick steel tubes with a maximum plate thickness of 67 mm and a diameter of 800 mm through the strong cold bending processing for $R/t = 5$. Such steel tubes are used in the space truss structure of Nagata Bridge in Tokyo (see Photo 8).

3.4 *The Increased Flexibility of Cutting Plans and Production Yield by Improving the Properties in the Transverse Direction*

The prescribed Charpy absorbed energy was defined as the value obtained from the transverse impact test. As a result, the production of bridge components became possible without applying any restriction on the cutting direction independently of the rolling direction. The production yields can be improved owing to the increased flexibility of the cutting plans.

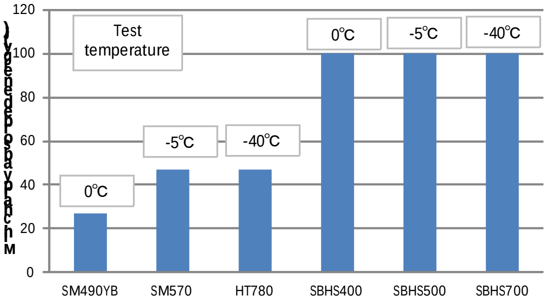

Figure 3. Charpy absorbed energy of SBHS

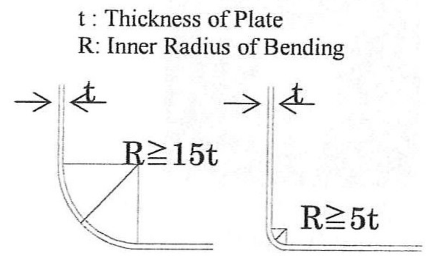

Figure 4. Minimum radius of cold bending

3.5 *The Quality Improvement in The Through-Thickness Direction (Sulfer Content: 0.006% Or Less, Improving the Resistivity Against Lamellar Tears)*

In bridge components, many joints are subject to the force applied in the through-thickness direction. Therefore, the properties in the through-thickness direction were also taken into account. In SBHS, the sulfur content, which influences the resistivity against lamellar tears, is lowered to 0.006% or less. Also, the characteristics in the through-thickness direction were set so as to satisfy the category Z35 of the JIS G3199 Standard, which is the highest level drawing ratio in the through-thickness direction.

3.6 *Safety Improvement for Preventing Brittle Fractures (100 J Or Higher Of The Charpy Absorption Energy)*

In general, many fatigue cracks are generated at weld toes on out-of-plane gusset plates. The cracks may propagate into the base material. The Charpy absorption energy of SBHS is higher than those of the previous steels, whose energies are 27 to 47 J. The high absorption energy increased the length of the critical crack of brittle fracture generation. As a result, SBHS can improve safety for greater fatigue cracks compared to the previous steels.

3.7 *Weathering Steel Specification*

The SBHS series include the weathering steel specification grades (a character “W” added to the end of the corresponding standard-type grade names), which cover both painted and unpainted bridges.

Photo 9. Rinkai Chuo bridge

4 APPLIED CASES AND THE ADVANTAGES OF THE SBHS

BHS, the predecessor of SBHS, was applied in 2006 for the first time for Rinkai Chuo Ohashi Bridge (see Photo.9). The bridge is 256 meters long and has a continuous steel orthotropic steel beck–box girder structure and three steel supports with a central span of 100 meters. The weight of the BHS500 used is 1,100 tons, which accounts for 29% of the estimated total weight of 4,000 tons. It is reported that the total steel weight was cut by 4% and the construction cost was reduced by 2% compared to the case where the common SM570 would have been used.

BHS500 is also used in Tokyo Gate Bridge (see Photo.10). The bridge has a truss–box girder hybrid structure with a length of 760 meters and a central span of 440 meters. The BHS500 used weighs 10,250 tons, representing 50% of the total steel weight of 20,460 tons.

The approach portions of the bridge have a steel floor slab–box girder structure with a span of approximately 70–120 meters.

Photo 10. Tokyo Gate bridge

The weight of the BHS500 used is 3,000 tons, accounting for some 20% of the total steel weight of 16,010 tons.

Approximately 14,000 tons of BHS steel has been used in the Tokyo Coastal Highway, which has a total steel weight of about 40,000 tons. Thus, BHS contributed to cutting the cost of the project as a whole. The Ministry of Land, Infrastructure, Transport and Tourism estimated that the total steel weight and material production cost of Tokyo Gate Bridge can be reduced by 3% and 12%, respectively, by using BHS steel.

In the case of Nagata Bridge in Tokyo (see Photo.8), the hybrid truss structure built with SBHS500 steel tubes not only improved the landscape by creating a transparent impression but also cut the cost by reducing the weight.

According to the trial design, it is also reported that the steel weight and production cost of girder bridges were reduced by using SBHS (Tominaga et.al.,2011). SBHS is also expected to lower the girder height.

5 CONCLUSIONS

The bridge construction has a significant impact on the development of society. This paper, briefly describes the history of the development of steel bridges in modern Japan and the impact of steels on it. The functions of newly developed high-performance SBHS steel and its impact on bridge construction are also mentioned. SBHS was developed to satisfy diverse requirements in recent bridge construction. Several Japanese bridges where the SBHS was applied are illustrated. The characteristics of SBHS were utilized for designing advanced bridges. SBHS has three grades classified by its yield strength ranging from 400 to 700 N/mm^2. By selecting the grade best suited to the purpose, SBHS is expected to further improve the cost efficiency and quality of steel bridges ranging from ordinary to large ones all over the world.

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