NIPPON STEEL & SUMITOMO METAL TECHNICAL REPORT No. 113 DECEMBER 2016

UDC 624 . 014 : 691 . 714

Technical Review

Advances in Steel Structures and Steel Materials in Japan

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Abstract

Since the first domestic construction of steel structures in the 19th century, Japan has applied various types of steel materials and members into infrastructures. Nowadays, Japan becomes one of the most advanced countries as for construction development of steel structures. This development is due to the spiral up evolutions between the research on steel materials and the construction of steel structures. This paper describes the history of innovation of high strength steel and seismic durability. In addition with the potential of steel material development, the future advance of steel structures is addressed.

1. Introduction

The Japanese construction stock has reached as high as 800 trillion yen at present, and a considerable amount of steel material is consumed every year. Approximately 25 million tons of steel is consumed in the construction field every year, occupying approximately 40% of the domestic ordinary steel demand. It equals the per capita steel consumption of 200 kg and is 2.5 times larger than that of USA. As a fact that approximately 30% of the Japanese buildings (in terms of total floor space) are of steel frame structure shows, the share of the steel structures in Japan is significantly higher when compared with those of foreign countries.

As for steel structures in Japan, 90 years after the building of the world's first cast-iron-built bridge, the Iron Bridge built in 1779, the Kurogane Bridge (cast iron) was built in 1868 and the first steel bridge Tenryugawa Bridge was built in 1888. Approximately 20 years after the constructions of the bridges, as a large-scale iron structure building, the Shimbashi Factory of the Railroad Bureau (combined use of cast iron and wrought iron) was built in 1889 and the Shueisha Printing Factory that used steel for the first time was built in 1894. Later, triggered by the completion of the then government-owned Yawata Iron and Steel Works that became the first Japanese integrated steel works (1901), Japanese steel structures significantly progressed and after the elapsed of time of more than 100 years, Japan has grown to be an advanced country in the world in the field of steel structure.

Although Japan has been attacked so frequently by huge earthquakes, it can be proud that large steel constructions are carried positively out as “the Akashi Kaikyo Bridge,” the longest suspension bridge in the world (central span 1 991 m) completed in 1998, “The Tokyo Skytree,” highest independent in the world (634 m) (2012), and “The Abeno Harukas” (2013) with the greatest height of 300 m. A factor that lies behind, and realized in succession, novel constructions worth becoming landmarks is the contribution of the technical innovations on the part of steel materials. In Japan, enhancement of steel material performance encouraged the development of steel structure constructions; conversely, new structure constructions have yielded technical innovations on the part of steel materials.

This report reviews the history of the development of the steel structure constructions in Japan and overviews the technical innovations on the part of steel materials that sustained the said development.[1] Furthermore, taking into consideration the potentialities that steel materials possess, possibilities of steel structures are surveyed.

2. Development of Steel Structure and Steel Material

2.1 The first steel structure using domestically produced member material

Until the end of 19th century of the Meiji Era, Japan imported steel materials from countries such as UK, Germany, and USA and relied much on the design technologies of foreign design engineers. For instance, the Ogura Repair Factory that was the first building built in the then government-owned Yawata Iron and Steel Works shown in **Photo 1** was built by the structural design and steel materials provided by Gütehoffnüngshutte AG.[2] The shop has been operated up to present and has been registered to one of the world heritages of “Industrial revolution heritages in the Meiji Era in Japan” this year, together with the former Head Office Building and others.

By the inauguration of the government-owned Yawata Iron and Steel Works in 1901, massive steel materials came to be produced domestically and the design technologies were enthusiastically absorbed and steel-framed structure factories all domestically de-

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signed, using domestically produced steel materials, came to be constructed. Alleged to be the first of such kind of factories is the Roll Lathe-turning Factory that was designed by Hitoshi Kageyama (later became the director of the Yawata Works), completed in 1909. **Photo 2**[2)] and **Fig. 1**[2)] show the entire view and a design drawing, respectively. The shop factory is a large factory measuring 20 m in span, 110 m in length, and 17.2 m in eaves height, of which columns are built up of channel sections and angle sections combined, and Z sections and angle sections are used for the main building and the furring strip, respectively. The roof truss is of pretty Fink truss structure composed of angle sections and equipped with crane girders built up with angle sections and steel plates.

Designing of steel structure constructions in dawn days of steel works construction owed greatly to the activities of young engineers who graduated from the department of mechanical engineering, department of civil engineering, department of architecture and building engineering, and so on. The technologies of steel structure construction so cultivated spread nationwide to naval arsenals, shipbuilding yards, and so on and lead the development of the steel structure technologies in Japan.[2)]

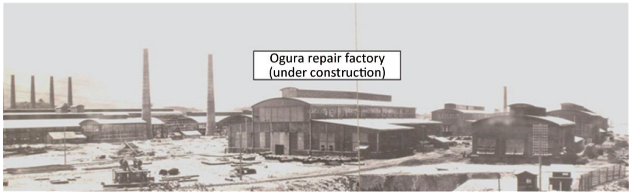


Photo 1 Construction of Yawata Steel Making Works (1900)[2)]

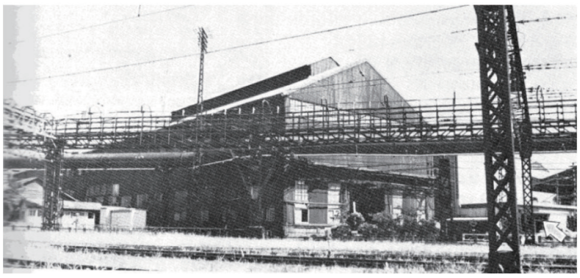


Photo 2 Roll Lathe-turning Factory (constructed in 1909)[2)]

2.2 Development of building, tower, and steel material

After the encounter with several wars afterwards, the Japanese steel frame structured buildings made rapid growth during the period of high-rate growth of Japanese economy in 1960s. The growth was also the history of battles against huge earthquakes and consequently, has realized high-rise buildings equipped with attractiveness together with robustness. Most of the Japanese buildings are below five stories, and similarly to the case of bridges, steel materials and technologies developed for high-rise buildings have come to be applied to medium- and low-height buildings sequentially and then steel frame structures have come to be used for buildings more widely.

In **Fig. 2**, the chronological transitions of the amount of steel frame production and the maximum heights of general buildings and freestanding-type towers are shown.[3)] The figure shows the history of domestic quantity of steel demands and the development history of maximum heights of buildings and towers with main major earthquake events.[4–6)] The steel frame production has reached a considerably high amount of over 6 million tons per year that had been maintained for almost 40 years. The amount of the production is over 10 times of that of the steel used for bridges. In 1990, the amount of the production of approximately 12 million tons was recorded, which is equivalent to the current crude steel production amount of a single country of UK.

In the general buildings, triggered by the abolition in 1961 of the 31 m restriction over building height, the Kasumigaseki Building of 156 m in height was built in 1968, exceeding 100 m in height. It was the opening of the high-rise building era in Japan. Later on, high-rise buildings such as the first main office building of the Tokyo Metropolitan Government Office, the Yokohama Land Mark Tower, and the Abeno Harukas (**Photo 3**), all of which can be considered to represent Japanese buildings, were constructed.[7)] Further-

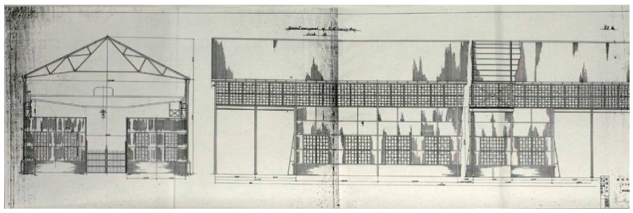


Fig. 1 Design drawing of Roll Lathe-turning Factory[2)]

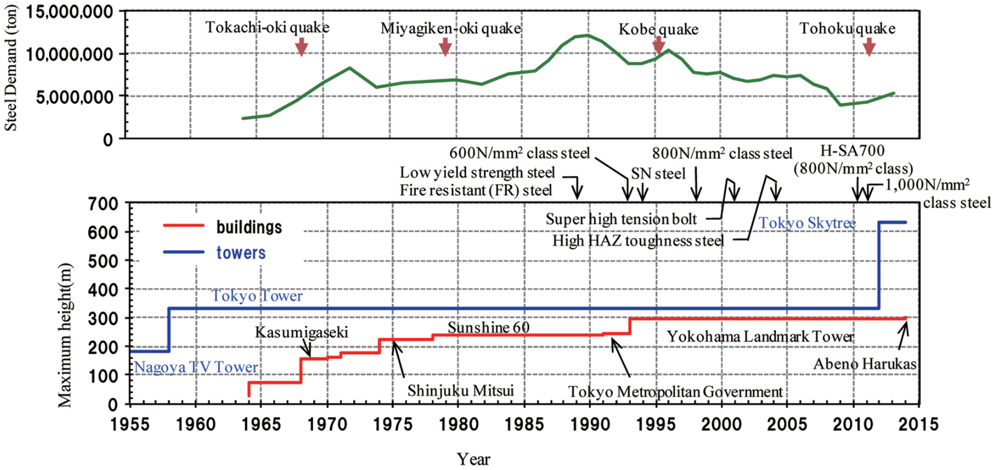


Fig. 2 Timelines of estimated steel demand and maximum heights of buildings and towers

more, as for freestanding-type steel tower, following the construction of the Tokyo Tower, then the tallest in the world, the Tokyo Skytree (**Photo 4**) was completed in 2012, which has become the tallest as an independent tower in the world.

However, the height of the Japanese buildings stagnates at 300 m at the highest, which is low ranked in the world. Furthermore, they do not have reached the height two times of those of the buildings built approximately 50 years ago. Although the restriction imposed by the Civil Aeronautics Law lies behind, there is a risk of frequent earthquakes in this country that rarely happen in other countries in the world. For this reason, application of high-strength steel to building steel frames was started belatedly following the application to bridges. A steel of tensile strength of 600 N/mm^2 class was applied to the Yokohama Land Mark Tower in 1993[8] and the steel of tensile strength of 800 N/mm^2 class was applied to the Kokura Station Building in 1998. Different from the steel materials specified for bridge use, both steel materials are specified for exclusive use for buildings, excellent in plastic deformability.

In around 2010, a new steel of tensile strength of 800 N/mm^2 class excellent in weldability and productivity and a steel of tensile strength of 1 000 N/mm^2 class that has the highest strength for building use were applied to actual buildings.[9] In particular, the steel of tensile strength of 800 N/mm^2 class contributed to the construction of the Tokyo Skytree, a steel tower proudly and freely standing as the highest in the world. On the other hand, around 1990, beside the trend of steel material strength growing higher, low yield strength steels (yield strength 100 N/mm^2 class steel and yield strength 225 N/mm^2 class steel) were developed for use as dampers as shown in **Photo 5**[10, 11] that enhanced aseismic performance. Furthermore in 2004, developed was the high heat affected zone (HAZ) toughness steel in which the toughness is secured in the weld HAZ even in high heat input welding.[12] As mentioned above, in the field of buildings, not only the steel materials with enhanced strength but also the steel materials with improved aseismic performance have been developed and provided energetically, and steel structures equipped with robustness for mega earthquakes are coming to be realized.

2.3 Development of bridge and steel material

Japan is composed of plurality of islands, and many rivers and mountains exist. For this reason, integrating the country by connecting roads and bridges became one of the important national policies. For the construction of long and large bridges that were energetically promoted, steel manufacturers have developed newest steel materials with all their might, of which results have come to be applied to general bridges sequentially. **Figure 3** shows the chronological transitions of the span of the representative ones of suspension bridges, cable stayed bridges, and truss bridges[13] in addition to the actual amount of accepted steel bridge order in Japan, and major steel materials and technologies developed and put into practical use.[14]

Photo 3 Abeno Harukas

Photo 4 Tokyo Skytree

Photo 5 Building with energy absorption dampers (buckling restrained braces)[10, 11]

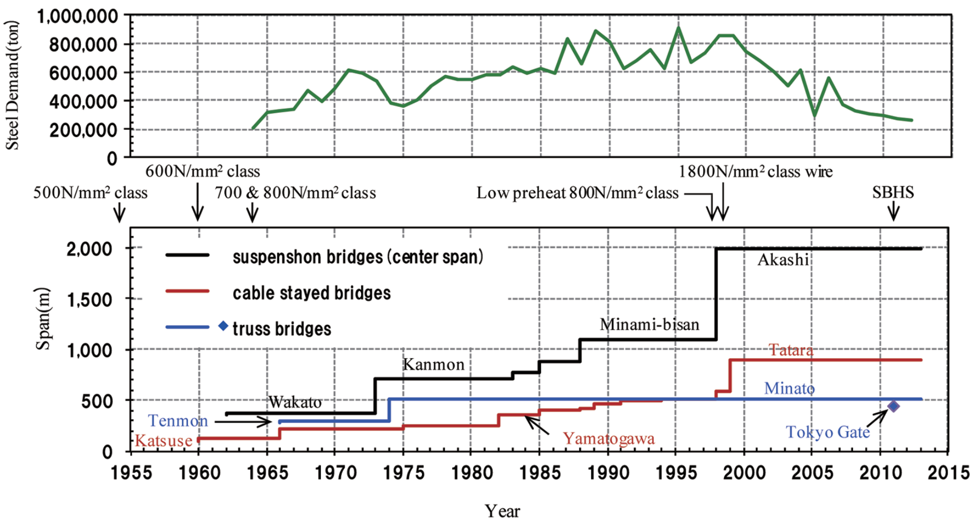


Fig. 3 Timelines of estimated steel ordered and maximum spans of bridges

Photo 6 Akashi Kaikyo Bridge (Courtesy of Honshu-Shikoku Bridge Expressway Company Limited)

Photo 7 Tatara Ohhashi Bridge (Courtesy of Onomichi Tourist Association)

For the period longer than 30 years from the latter half of 1960s to early 2000s, approximately 500 thousand tons of steel materials were used for bridges annually. In 1990s, the highest annual steel material amount of 900 thousand tons was recorded. Along with the active bridge construction, extension of spans of suspension bridges, cable stayed bridges, and truss bridges were attempted, and, presently, the span has reached as long as 2000 m, 900 m, and 500 m, respectively. All of them ranked first or third in the world when they were constructed, and even at present, in the suspension bridge category, the Akashi Kaikyo Bridge (**Photo 6**) ranks first in the world, in the cable stayed bridge category, the Tatara Ohhashi Bridge (**Photo 7**) ranks fifth in the world, and in the truss bridge category, the Minato Ohhashi Bridge (**Photo 8**) ranks third in the world. What sustained the extension of the bridge spans is the excellent performance of Japanese steel materials.

In the early planning stage of the Akashi Kaikyo Bridge, there existed a problem of increase in construction cost and increase in dead weight as two cables on either side totaling four in all became necessary when the steel wire of conventional tensile strength steel (1600 N/mm^2) was used. What solved the problem was the high-strength steel that achieved 1800 N/mm^2 class with the increase by 200 N/mm^2 at a burst and this enabled the construction of the longest-in-the-world huge bridge (completed in 1998).[15] Presently, steel wire of 2000 N/mm^2 class has been already developed and now is the era in which the construction of a suspension bridge with the central span exceeding 2000 m is possible.[16]

As for the plates to be applied to bridge girders and the like, a steel of tensile strength of 500 N/mm^2 class was applied (The Sagami Ohhashi Bridge) in 1954. Later on in 1960, a steel of tensile strength of 600 N/mm^2 class was applied and has come to be widely used (The Nishimura Bridge, The Hirano Bridge). In 1974, a big amount of steels of tensile strength of 700 N/mm^2 class and 800 N/m^2 class was used for the Minato Ohhashi Bridge and the domestic record of the span of truss bridges maintained at the time was renewed by two times at a burst.

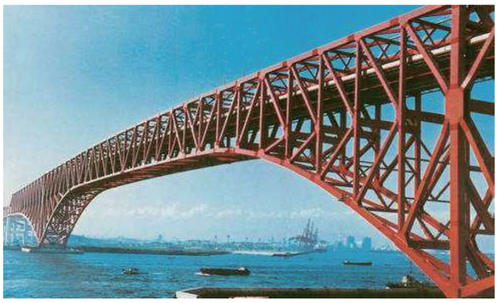


Photo 8 Minato Ohhashi Brige (Courtesy of Japan Bridge Association Inc.)

(a) Panoramic view (b) Welded panel point

Photo 9 Tokyo Gate Bridge

In the construction of the Akashi Kaikyo Bridge, as needs for enhancing the productivity of the stiffening girder arose, a steel of low-temperature preheating-type plate of 800 N/mm^2 class was developed and contributed to the enhancement of the productivity of bridges greatly. Triggered by the development, after the latter half of 1990s, a high-performance steel SBHS steel (yield strength 500, 700 N/mm^2 class) was developed to realize simultaneously the steel with higher strength, higher toughness, and higher weldability and standardized and was applied massively to the Tokyo Gate Bridge that was completed in 2012. With the advent of a high-performance steel equipped with excellent weldability, in the construction of the Tokyo Gate Bridge, fully weld-built-up sections without using bolts were employed for the first time in the construction of a large-scale truss bridge.[17, 18] It is an example of steel materials providing structural prettiness. In **Photo 9**, the entire view of the Tokyo Gate Bridge and a welded panel point are shown.

3. Steel Material that Contributed to the Development of Steel Structure Construction

Coupled with vigorous steel structure constructions, in the past several tens years, novel materials were developed and applied to actual use. **Table 1** shows the major characteristics of the steel materials developed in Japan. Owing to the innovation of production technologies, the versatility of strength such as enhanced strength or lowered strength, the versatility of functionalities such as weldability and deformability, and the versatility of sizes of steel materials have been rapidly expanded. In this chapter, Japanese characteristic steel materials for structural use are introduced.

3.1 High tensile strength steel (heavy plate, cable, and high-tension bolt)

3.1.1 Steel material (heavy plate)

In **Fig. 4**, the chronological transitions of the application of high tensile strength steel to bridges and buildings are shown. As the demand for construction of huge and long bridges arose first, the application of high tensile strength steel to bridges preceded and later

Table 1 Major characteristics of steel materials developed in Japan

Characteristics	Strength versatility	Function versatility	Section versatility
Material features	• Extra high strength (1 800 N/mm² class cable wire and 1 400 N/mm² bolt) • Hihg strength (plates with tensile strengths of 600 to 1 000 N/mm²) • Low strength (plate with yield strengths of 100 to 225 N/mm²)	• High weldability • Low yield-to-tensile strength ratio (low yield ratio) • High fracture toughness • Narrow yield strength range • High geometrical accuracy	• Thick plates and sections • Lage sections
Production technologies	• Advanced metallurgy (microstructure control and strength ening technologies)	• Thermo mechanical control process (TMCP) • Advanced smelting and refining technology	
		• Advanced rolling technology	

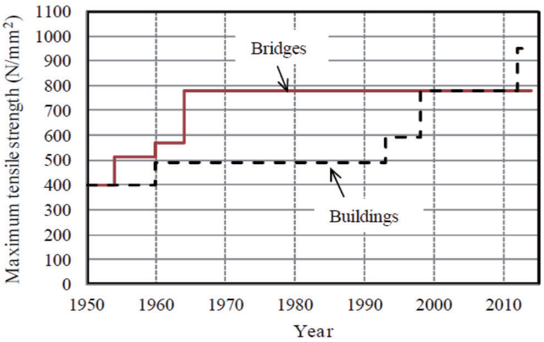


Fig. 4 Timeline of maximum tensile strength

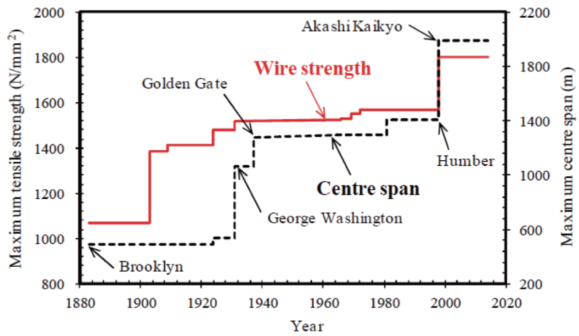


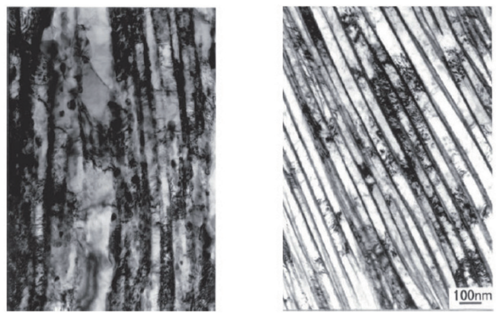
Fig. 5 Timeline of wire strength and center span

on the application to buildings was developed. Since bridges were based on elastic design until 1960s, the application of steel up to the tensile strength of 800 N/mm² class was promoted. These high-strength steels relied entirely on the traditional method of increasing the carbon content and the addition of alloy elements like Ni.

On the other hand for buildings, deterred by the concern about the effect on aseismic performance and the shift from elastic design concept to plastic design concept in 1980s, the application of high-strength steel to buildings was advanced in a careful manner. In the latter half of 1980s, the performance required to building materials was extensively studied and excellent plastic deformability performance came to be demanded to steel materials for buildings in later 1980s.[4, 5, 19] Therefore, it was after 1990s that the application of high tensile strength steel progressed. After 2000s, what was put into practical use was the damage control structure system that restrains the damage of columns and beams by absorbing the seismic energy with dampers.[20] With this, the application of the steel materials of tensile strength of 950 N/mm² class to actual use was attempted. Although the plastic deformability of the high-strength steel is smaller than those of the conventional steels, the performance of the entire building is secured with combined use of dampers. It is considered as an example of a case wherein the optimized combination of a structural system with steel materials was applied.

3.1.2 Steel wire for cable

In **Fig. 5**, the transitions of center span of suspension bridges in the world and the cable wire tensile strength are shown. Owing to the drastic increase in the wire strength, the construction of the Akashi Kaikyo Bridge having the longest central span in the world became possible. Generally, high strength of steel wire is realized by increasing the carbon content to approximately 0.8% and by the pearlite structure formed by a stratified microstructure of hard material layers and soft material layers. The spacing between the hard material layer and the soft material layer is called lamellar spacing. The cold drawing work and the heat treatment to more clearly form the lamellar microstructure and to further reduce the spacing are fundamental to realize the high strength.



(a) Conventional (b) Added with Si and Cr

Photo 10 Differences of wire configuration

The steel wire is hot-dip-galvanized to enhance corrosion resistance. However, there is a problem of collapse of the lamellar structure due to the thermal influence of the galvanizing process and it was the deterring factor for increasing strength (**Photo 10** to be referred). A fact that the lamellar structure can be maintained with the addition of Si was found, leading the way to the practical application of the unprecedented high-strength steel wire. At present, based on the observation on the atomic level, it is now known that Si suppresses the diffusion of carbon from cementite (carbon compound).[21] The high-strength wire of finely stratified microstructure can be worth being called a "natural composite material."

3.1.3 High tensile strength bolt

It was in 1958 when high tensile strength bolts came to be used to substitute rivets for the first time in Japan. In **Fig. 6**, the transition of the maximum tensile strength of the bolt is shown.[22, 23] The bolts of tensile strengths of 700 N/mm^2 class to 1300 N/mm^2 class were standardized in 1964. However, a problem of hydrogen embrittlement appeared soon after in the 1300 N/mm^2 class and the maximum strength stagnated at 1100 N/mm^2 class. Later, the problem of the hydrogen embrittlement also appeared in 1100 N/mm^2 class, and after 1979, only classes up to 1000 N/m^2 class were standardized. Enhancing bolt strength stagnated for 20 years due to the fundamental problem of the hydrogen embrittlement.

The problem of the hydrogen embrittlement was solved in 1999. A bolt having the strength improved by 400 N/m^2 (SHTB) was developed.[22] The brittleness of the bolt is caused by the hydrogen produced by the corrosion of the bolt, penetrating into the steel material, moving to the stress-concentrated area and accumulated therein (**Fig. 7**). Accordingly, the problem of the hydrogen embrittlement was intensively studied and finally solved by relieving the stress concentration due to optimization of the bolt shape and by forming alloy carbides of Mo and V that can trap the hydrogen in the steel material.

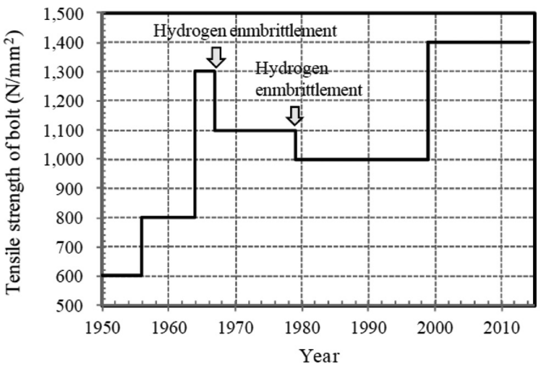


Fig. 6 Timeline of maximum bolt strength

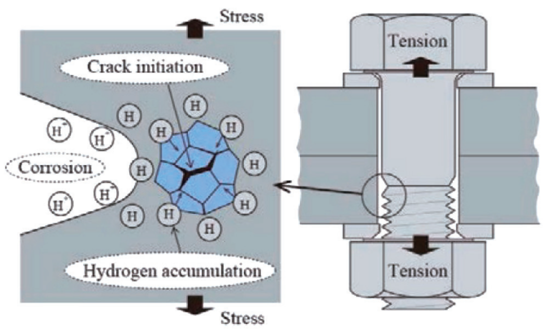


Fig. 7 Mechanism of hydrogen embrittlement

SHTB has been widely applied to buildings for more than 10 years up to present. Presently, the technology is highly evaluated as contributing to the manpower saving in the steel structure construction work and has come to win general recognition.

3.2 High-performance steel for bridge

Although the application of high-strength steel to bridges rapidly progressed in 1960s, since the steel contained high contents of C and B to secure hardenability, there existed a problem of poor weldability like low temperature cracking. For this reason, the steel provided a need of preheating operation of up to 100°C or higher, and a low-temperature preheating-type steel (800 N/mm^2 class) was developed. **Figure 8** shows the transition of C_{eq} of 800 N/mm^2 class steel material for bridge use and it is known that the rapid chronological decrease has been realized owing to the development of purification technologies of steel materials.[24]

For steel materials for bridge use, improvement of the performance of strength and weldability to higher level were promoted. However, strength and weldability are not all of the required performances. Triggered by the research on high-performance steel materials for bridge use in USA in 1992, the research on high-performance steel materials for bridge use was started in Japan in 1994. As required performance, in addition to yield strength and tensile strength, fracture toughness, weldability, cold workability, and further weather-resistant characteristics were designated and, as steel materials for exclusive use for bridges, SBHS400, 500, and 700 (figures denoting yield strength) were developed. In 2008, SBHS500 and 700 were accredited as the new steel material standard (JIS G 3140-SBHS), and, in 2012, SBHS400 was newly incorporated.[18] The steel in which the strength and the toughness are compatible was realized by refining the microstructure by the thermo-mechanical control process (TMCP) described later. Steel materials of the same characteristics with that of SBHS were applied to the Tokyo Skytree.[19]

High-performance steels for bridge use have been already standardized in USA and Korea, whereas, as shown in **Table 2**, the guar-

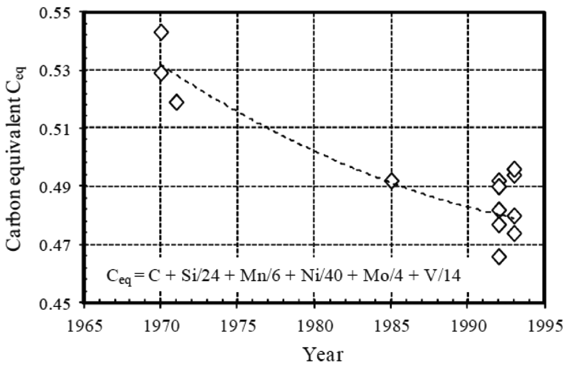


Fig. 8 Chronological trend in C_{eq}

Table 2 Comparison of high performance steels for bridges

Country	Specification	Yield strength	Tensile strength		Charpy impact test		
		Minimum (N/mm^2)	Minimum (N/mm^2)	Maximum (N/mm^2)	Minimum (N/mm^2)	Temperature (°C)	Specimen direction
Japan	JIS G 3140 SBHS500	500	570	720	100	−5	Transverse
USA	ASTM A709 HPS485W	485	585	760	34	−23	Longitudinal
Republic of Korea	KS D3868 HSB500	450	600	N.A.	47	−5	Longitudinal

anteed values of the yield strength of Japanese SBHS are higher than those of USA and Korea.[18] As for toughness as well in SBHS, the test specimen is taken in the transverse direction in a strict manner and furthermore, the guaranteed values are higher. Generally, Japanese SBHS has higher performance.

3.3 Aseismic steel

In 1982, the aseismic design method of buildings was greatly altered from the elastic design concept to the plastic design concept. In company with the alteration, for exclusive use for buildings, steel materials (SN steel, SA440 steel, and the like) appropriate for securing plastic deformability of steel frames were developed.[4, 5, 19] The steel materials have the toughness values and strength through thickness direction specified in the bridge design code. Furthermore, the aseismic steels are characterized by the definitions of (1) the upper limits of yield ratio (ratio of yield strength vs. tensile strength) and (2) the upper and the lower limits of yield strength.

The yield ratio is a performance index that is directly linked to the deformability of member materials.[25] As the simple mechanical model in **Fig. 9** shows, L_p, the spreading range of plasticity when the beam end reaches a critical condition, is correlated to the yield ratio YR and the lower the YR is, the larger the beam plastic deformation range becomes. Therefore, for steel materials of tensile strength of 400–600 N/mm^2 classes, the specification of yield ratio YR of 80% or below was provided. The steel material of low yield strength (YP) is produced by controlling the microstructure and by controlling the grain size of the microstructure on the basis of dual structure of hard microstructure and soft microstructure, the required strength and YR were realized.

On the other hand, the range of the upper and the lower limits of yield strength is a performance index that influences the deformability of the entire framed structure. As shown in **Fig. 10**, a mechanism that develops plastic deformation of beams prior to plastic deformation of columns enhances the deformability of the entire framed structure.[26] In order to guarantee the precedence of the beam plastic deformation, it is necessary to limit the scattering of yield strength. For this reason, in the steel materials of tensile strength of 400–600 N/mm^2 classes, a provision of limiting the yield strength to a certain range of 100–120/Nmm^2 was introduced.[27]. The control of the upper and the lower limits of yield strength has been realized by the sophistication of production process control.

Provisions of yield ratio and the upper and the lower limits of yield strength were specified by Japan, leading the world, as a message demanding higher performance. In **Table 3**, shown is the comparison of the performance specifications of steel materials at a similar strength level used in aseismic design in major countries. It is known that both yield ratio and toughness in the Japanese standard are most stringent. Furthermore, in the European standard, the upper limit of yield ratio is not specified, leaving a room for further study.

4. Production Technology that Sustained the Development of High-performance Steel Material

The production technologies that sustained the Japanese high-performance steel materials are as follows: (1) high purification of steel material, (2) metallurgy that controls microstructure, and (3) refining of microstructure by the TMCP technology.[28] The properties of steel material are influenced strongly by the contents of carbon, sulfur, phosphorous, and so on, which are unavoidably contained in the steel material in the production processes. In Japan, based on the optimized contents of these elements, technologies that control material properties by controlling the microstructure by means of leading metallurgy and the TMCP technology have been developed. Most characteristic technology is the TMCP technology (**Fig. 11**).[29, 30]

The TMCP technology is a technology that provides high strength and high toughness compatibly by realizing fine microstructure, basically, in an "as-rolled state" through the control of the

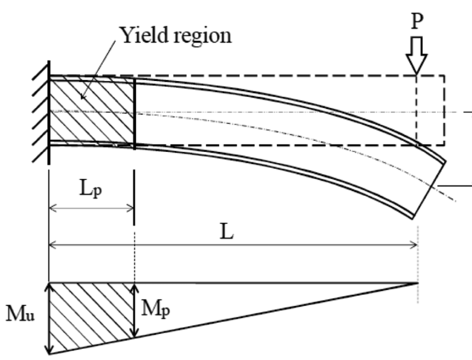


Fig. 9 Yield spreading in cantilever beam

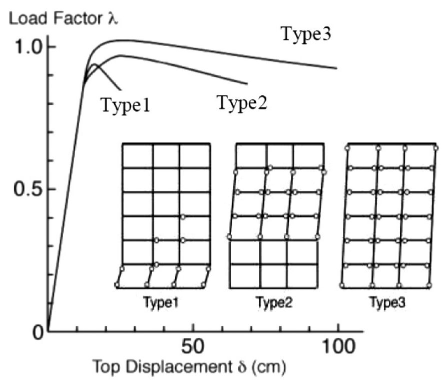


Fig. 10 Collapse mechanisms and their deformation capacity[26]

Table 3 Comparison of steel specifications for seismic design

Country or region	Specification and designation	Yield strength Minimum (N/mm^2)	Yield strength Maximum (N/mm^2)	Maximum yield ratio	Charpy impact test Charpy energy (J)	Charpy impact test Temperature (°C)
Japan	JIS G 3136 SN490B	325	445	0.8	27	0
USA	ASTM A992	345	450	0.85	27 *2	21 *2
Europe	EN-10025 S355JR	355	N.A.	0.91 *1	27	20

Note: *1 Maximum yield-to-tensile strength ration is required not in the EN-10025 but in Eurocode 3

*2 Supplemental requirements

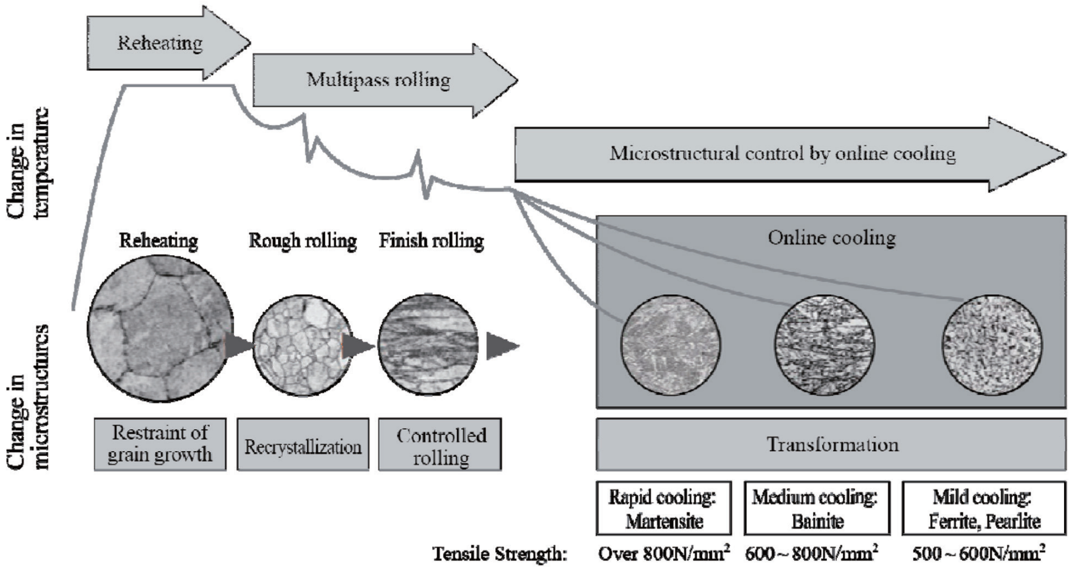


Fig. 11 Outline of thermomechanical control process (TMCP)[29, 30]

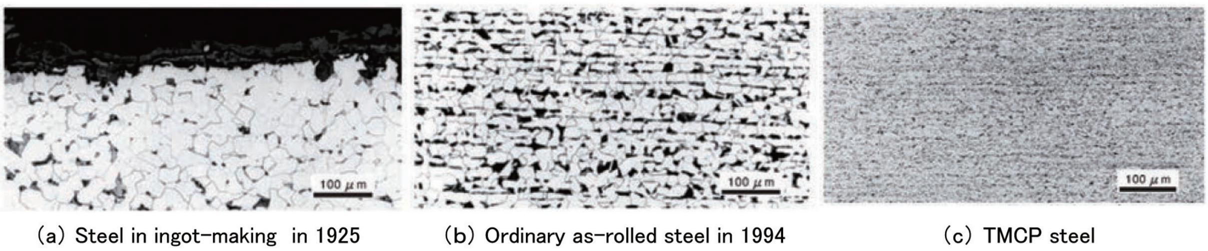


Photo 11 Comparison of microstructure of steels made by different production processes

chemical compositions of steel, heating temperature, rolling conditions, and cooling conditions.[31] The TMCP technology is the combination of the "controlled rolling" that promotes refining of microstructure by introducing dislocation in the high temperature range and the "accelerated cooling" that realizes quenching effect while suppressing the growth of grains. Owing to the technology, with lessened contents of carbon and alloying elements, high-performance steel materials excellent in weldability can be manufactured with high productivity. In **Photo 11**, for comparison, microstructure photographs of TMCP steel, ordinary steel material for welded structure use and the steel material produced in 1925 are shown.[32] The grain size of the ordinary steel is approximately 20 μm, which is refined to approximately 5 μm by the TMCP.

In **Fig. 12**, sulfa contents of 400 N/mm^2 class steel samples taken from actual railroad bridges are shown and it is known that the sulfa content rapidly decreases chronologically along with the development of material purifying steel making technology.[33]

5. Potentiality of Steel Material and Further Development of Steel Structure

Figure 13 is a schematic drawing of the ranges of tensile strength of major industrial materials.[34, 35] Though the steel material strength of the bulk materials like heavy plates is 400–600 N/mm^2, steel materials have a strength range of 200–4000 N/mm^2 when wire rod is included. When compared with other materials, the strength ranges of carbon fiber and steel material are remarkably

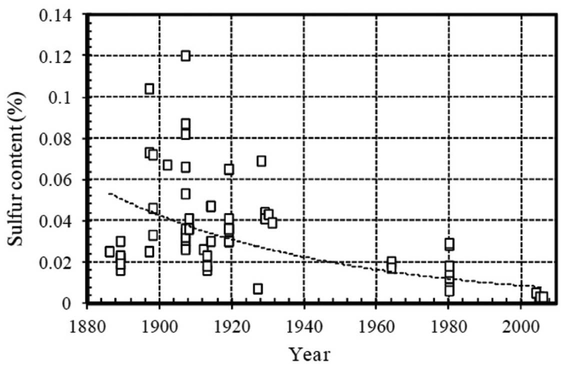


Fig. 12 Chronological change in sulfur content

wide. This is because of that steel material is the alloy of iron and carbon and has the characteristic of developing phase transformation by the cooling from high temperature state. By changing the carbon content or the cooling rate, various transformed microstructures can be obtained and as a result thereof, steel materials can produce various material characteristics. Furthermore, the ultimate strength of steel material can reach as high as 10000 N/mm^2 or higher. Steel materials are on the incessant process of development and they can be termed as "new material" implying big potentiality.

In the automotive industry, to comply with the strong needs of lighter-weighted-body cars, the tensile strength of steel materials has been rapidly enhanced in the past ten and several years.[36] The

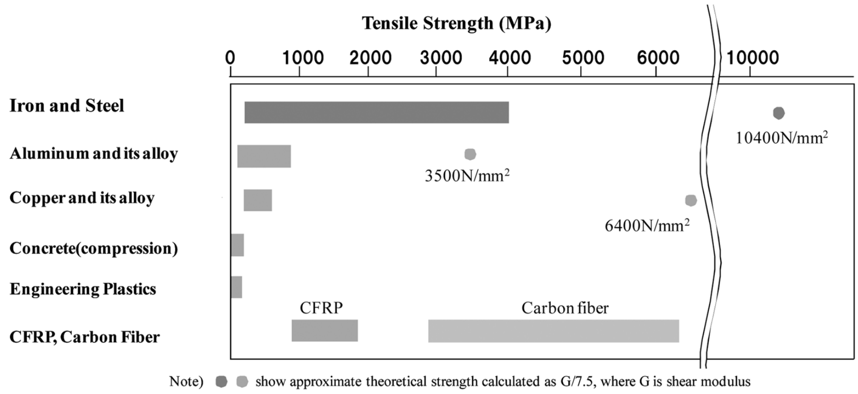


Fig. 13 Comparison of tensile strength of various industrial materials

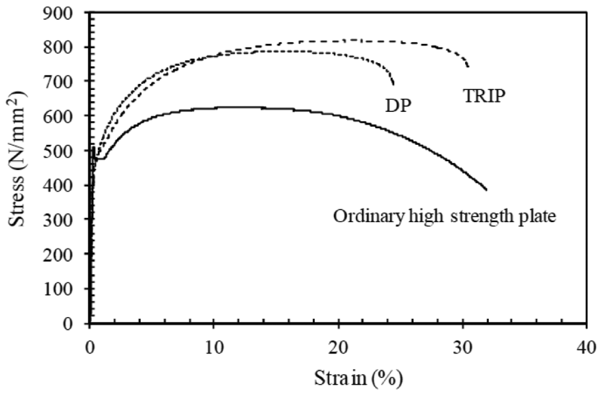


Fig. 14 Comparison of stress-strain relationships

tensile strength of the steel materials that used to be 400 N/mm^2 class in the latter half of 1990s has been enhanced to 1 200 N/mm^2 class up to present. The high strength like this was achieved by the development of new steel materials like dual phase steel (DP steel) that has a composite structure of hard material and soft material, and TRIP steel that has martensitic transformation induced plasticity effect of instable austenite (**Fig. 14**).[37] Presently, a steel of tensile strength of 1 000 N/mm^2 class having large elongation performance of 25%–30% is reported. Furthermore, by utilizing hot press called hot stamping, high strength of 1 500 N/mm^2 or higher (1 800N/mm^2 in part) has been realized,[38, 39] and the rapid progress of steel materials is ongoing.

As mentioned above, vigorous challenge to improving steel material performance in the field of automotive industry is being incessantly made. On the other hand, the research and development are being promoted aiming at steels with higher tensile strength,[40] higher Young's modulus,[41] and higher durability that restrains fatigue crack propagation,[42] and the development of these new steel materials will be a driving force to further expand the potentiality of steel structures.

When eyes are turned to structural constructions that form social infrastructures, existence of various social needs and views thereon are found. Major concerned subjects are ever growing natural disaster risks (seismic motion, landslide disaster, flood, tsunami, liquefaction, and volcanic eruption), manmade disaster risks including terrorism and the like (traffic accident, large-scale fire, and explosion), countermeasures for deterioration in structural constructions including industrial infrastructures (deterioration diagnosis, LCCA, and asset management), subjects to realize sustainable societies (diversified utilization of various energies, energy saving, environmental conservation, and environmental improvement for more comfortable life), declining birth rate and growing aging population, labor shortage (manpower saving in construction work, robotization, and supply of appropriate materials from various kinds), exploitation of new space to meet the sophistication of social life (ocean, deep sea, great-depth underground, ultrahigh-rising, and space), and the evolution of construction software and technologies to global markets. These subjects are considered to be termed as “a group of subjects in a wide range” that requires the development of business model necessitated depending on cases in addition to the development of revolutionary materials and structure technologies (structure system, design, and evaluation technologies).

Presently, the group of these diversified and varied subjects is treated as domestic technical subjects, however hence forth, along with the expansion of the market in South East Asian countries, the subjects will become inevitably global ones. The stage where steel materials play an important role is considered to further expand and it is foreseen that further diversification and higher performance (strength, rigidity, energy absorption capability, corrosion resistance, fire resistance, and so on) will be sought after to steel materials.

6. Conclusion

In this article, the development of steel structure constructions and innovation of steel materials in Japan have been reviewed. Through the review, it is known that in Japan, enhanced steel material performance encouraged steel structure constructions to jump and further conversely, new structure constructions have yielded technical innovation of steel materials. As for buildings, accompanied by the trend in high rising of buildings, the strength of steel materials was enhanced, and developed was the steel materials excellent in seismic resistance in which the upper limit of yield ratio and the validation limit of yield strength are specified. As for bridges, as observed from the relationship between the central span of suspension bridges and the wire strength, the enhanced strength of the steel material sustained the elongation of the span of bridges and spurred on the trend.

Furthermore, as a representative manufacturing technology that sustained the development of various high-performance steel materials that Japan put into practical use in the very early period, the TMCP technology was introduced. It was shown that, with the research examples of high tensile strength steel in the automotive field, the strength potentiality of steel material is still high and it is a "material" on the way of further development. The high-performance steel developed in Japan will contribute to the growth of construction market expected to expand globally hereafter with newly emerging countries situated in its center, and the authors expect that "the partnership of steel structure and steel material that yielded innovation on either side" that was once observed in Japan will be widely evolved to the world.

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