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ADVANCES IN STEEL STRUCTURES AND STEEL MATERIALS IN JAPAN

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Abstract: There are around six hundred thousand buildings that are built every year in Japan, and approximately 40% of them are constructed using steel frames. This wide application of steel frames is largely because of the continuing technological advancements in structural steel systems and steel materials for meeting a variety of needs that have evolved in the market. In this paper, starting with an overview of steel buildings in Japan, some of the advanced steel materials such as high-strength steels and seismic resistant steels are outlined with their backgrounds. Since the material advancements in Japan are largely motivated by frequent large earthquakes, the relations with seismic design are stressed throughout the paper.

1. Introduction

Although the production and application of iron and steel were delayed by about 100 years in Japan compared with those in Europe and the US, Japan is one of the most advanced countries in both steel production and application at present. This was made possible because of extensive R&D activities on technologies for production of steel, steel materials, and various structural steel systems. Since Japan is one of the most seismically active areas in the world, steel structures have played an important role in securing safety against frequent and large earthquakes that have left tremendous damage and human losses in the past.

Japan domestically consumes about 50 million tons of steel every year, and approximately 45% of the steel is used for the construction market. Although Japan has been reaching an economically mature stage, the Japanese industry of steel and steel structures may expect further growth in steel consumption for buildings and infrastructure because of strong current demands for renovations, renewals, and even urban redevelopment.

In this paper, starting with the overview of steel buildings in Japan, development of some of the advanced steel materials including high-strength steels and seismic-resistant steels is outlined in detail with their backgrounds. Some of the advancements are motivated by frequent large earthquakes; therefore, the relations with seismic design are stressed.

2. Steel building market overview

Based on the recent statistical data in 2016, approximately 22 million tons of steel is used in the whole construction market in Japan. Among that, the building market covers a large portion, which is about 15 million tons. For steel building frames, the steel used for the main members is estimated to be five to six million tons. Steel plates, hot-rolled steel shapes, and cold-formed steel members are the major steel products and members used.

Fig. 1 indicates the steel consumption statistics by number of stories built using steel frames. Although one may imagine that steel frames are mainly applied to high-rise buildings, the majority of them are used in the low-to-medium rise category, buildings in which have five or less than five stories. Some sources say that there are roughly 100 thousand design offices, 500 thousand general contractors, and 20 thousand fabricators working under the building market in Japan.

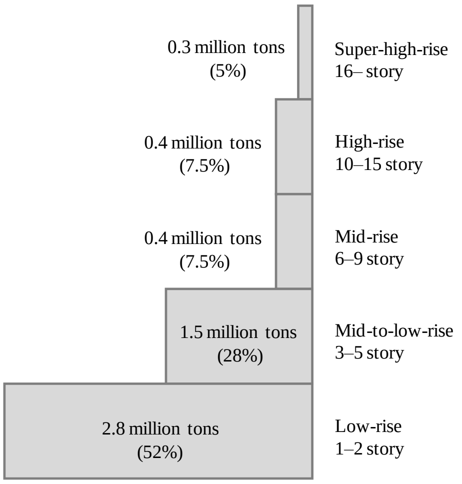

Fig. 1 Steel used by number of stories

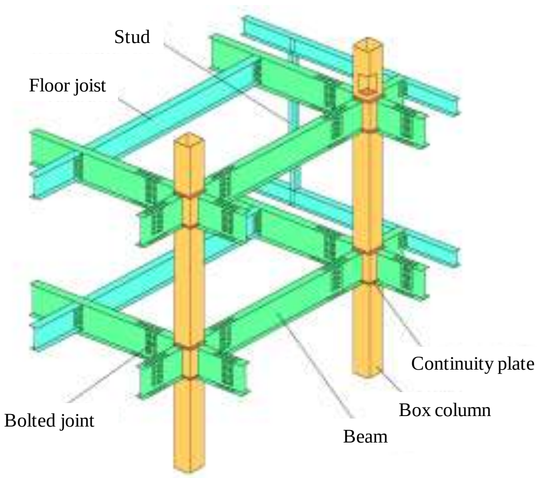

Fig. 2 Typical frame system in Japan

There are several structural types for steel building frames used in Japan. The type that is encountered most often is shown in Fig. 2. The frame system designed in Japan can be characterised by the following technical terms: a two-directional rigid frame, box-shaped steel columns, and welded beam–column connections. At the connections, beams and columns are fully welded and stiffened using continuity plates. This design practice, especially with box columns, may have evolved from a seismic-design consideration, in which robustness should be secured against extreme earthquakes in all directions.

3. Steel buildings and steel materials

The construction of steel buildings in Japan has rapidly grown since the 1960s. Fig. 3 shows the maximum heights of buildings and self-standing towers and the historical timeline of the estimated steel demand for buildings [1,2]. Steel material developments and earthquakes are also indicated in the figure. As seen, a large number of steel frame buildings have been constructed in Japan. The number peaked in 1990 at about 12 million tons, which is large and is comparable to the present crude steel production of the UK.

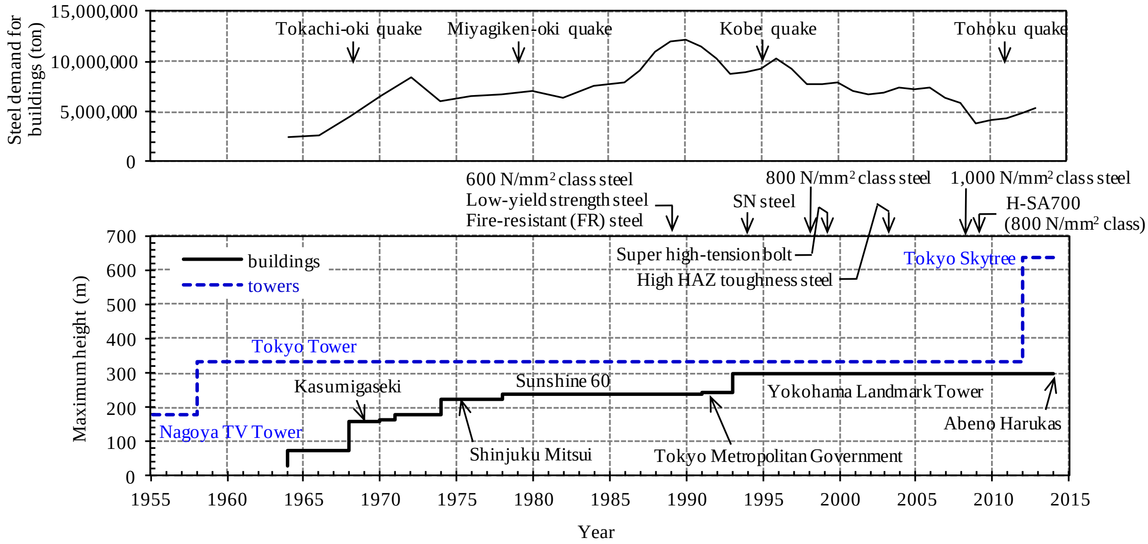

Fig. 3 Timelines of steel demand and maximum heights of buildings and towers [1,2]

Starting with the construction of the 156-m high Kasumigaseki Building in 1968, symbolic high-rise buildings have continued to be built, including the Yokohama Landmark Tower (1993) and the recent Abeno Harukas (2014), both with a height of about 300 m. As for self-standing towers, the Tokyo Tower, the world's tallest tower at that time, was constructed in 1958. Then, in 2012, the Tokyo Skytree was built and brought the record for the tallest building back to Japan. It should be noted that the maximum height of buildings in Japan still remains 300 m and is far less than the height of the world's tallest building. This relatively low height is mainly due to the high seismic risk in Japan.

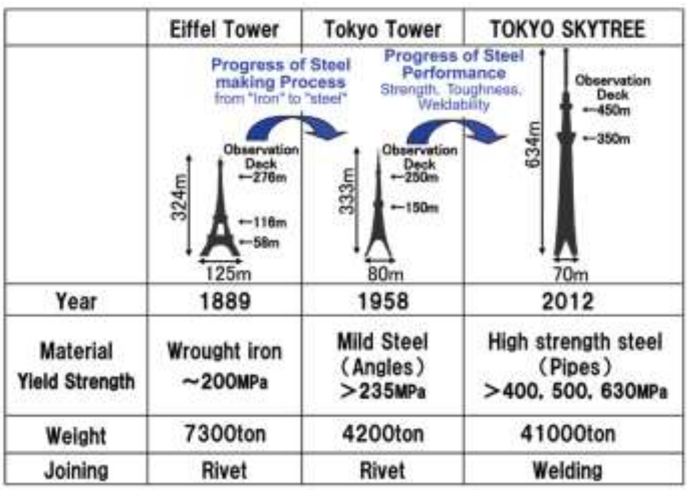

Fig. 4 Comparison between famous towers of the world [3]

As seen in Fig. 3, various high-performance steels were developed including high-strength steels that made construction of high-rise buildings possible. Fig. 4 shows a comparison between the Eifel Tower, the Tokyo Tower, and the Skytree Tower, indicating how building materials have contributed to realizing the tallest self-standing towers in the world [3]. The figure shows that advancement of building materials from wrought iron to high-strength steels has contributed to the increase in height, together with progress of joining technology from rivet to welding.

Coupled with the vigorous construction of steel structures in Japan, various innovative steel materials have been developed, especially over the past few decades. Fig. 5 shows the major characteristics of the steels developed in Japan [1,2]. The steels have “strength versatility” from high strength to low strength, “function versatility” such as weldability, fracture toughness, and deformation capacity, and “section versatility” with a variety of sectional sizes. Later in this paper, some of the representative steels will be outlined in detail.

Characteristics	Strength versatility	Functional versatility	Section versatility
Material features	• Extra-high strength (1,800 N/mm^2 class cable wire and 1,400 N/mm^2 bolt) • High strength (plates with tensile strengths of 600 to 1,000 N/mm^2) • Low strength (plates with yield strengths of 100 to 225 N/mm^2)	• High weldability • Low yield-to-tensile strength ratio (low-yield ratio) • High fracture toughness • Narrow yield strength range • High corrosion resistance • High fire resistance	• Thick plates and sections • Large sections
Production technologies	• Advanced metallurgy (microstructure control and strengthening technologies)	• Thermomechanical control process (TMCP) technology • Advanced smelting and refining technology • Advanced rolling technology	

Fig. 5 Major characteristics of steel materials developed in Japan [1,2]

4. High-strength steels

Fig. 6 shows the chronological trends of the maximum tensile strength (TS) of steel plates used in bridges and buildings in Japan [1,2]. It can be seen that the application of high-strength steel advanced for bridges with the growing need for long-span bridges, and it was then expanded for use in buildings. Steel plates with a TS of 800 N/mm^2 were successfully applied in the 1960s for construction of bridges; however, the application of high-strength steel in buildings lagged behind their application in bridges because of the concerns about the frequent large earthquakes.

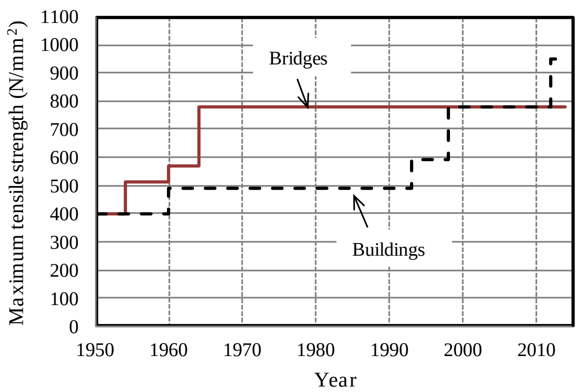

Fig. 6 Timeline of maximum TS [1,2]

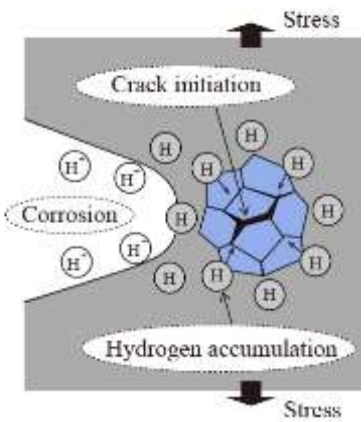

Fig. 7 Hydrogen embrittlement [2]

With the change in seismic design for buildings in 1981, the requirements of structural steel for the new seismic design were studied in the late 1980s. After development of new steels for the seismic design, progress was made in the application of high-strength steels with maximum TSs up to 800 N/mm^2 for buildings during the 1990s. Subsequently, the TS surpassed that of bridges to 1,000 N/mm^2 in the early 2010s, once a new seismic-resistant system, which has been mentioned later in this paper, became common. Note that the TSs for steel structures are 550 N/mm^2 in EN (S450J0) and 620 N/mm^2 in ASTM (A913 Gr 70); therefore, utilization of high-strength steels for steel structures is quite outstanding in Japan.

Apart from steel plates, exceptionally high-strength steels were developed for wires and rods. One example is the new high-tension bolt called super high-tension bolt (SHTB) developed in 2001 [1,2]. It does not suffer from hydrogen embrittlement that has hindered the strength increase of steels, and as a result, it achieved a dramatic strength increase of 400 N/mm^2 to realize a TS of 1,400 N/mm^2. Fig. 7 shows the mechanism of hydrogen embrittlement; hydrogen produced by corrosion penetrates inside the steel and makes the regions of stress concentration brittle. The SHTB was developed by alleviation of stress concentration and material property improvement against fracture. Note that the maximum strength of high-tension bolts for steel structures is 1,040 N/mm^2 in Eurocode 3 and ASTM.

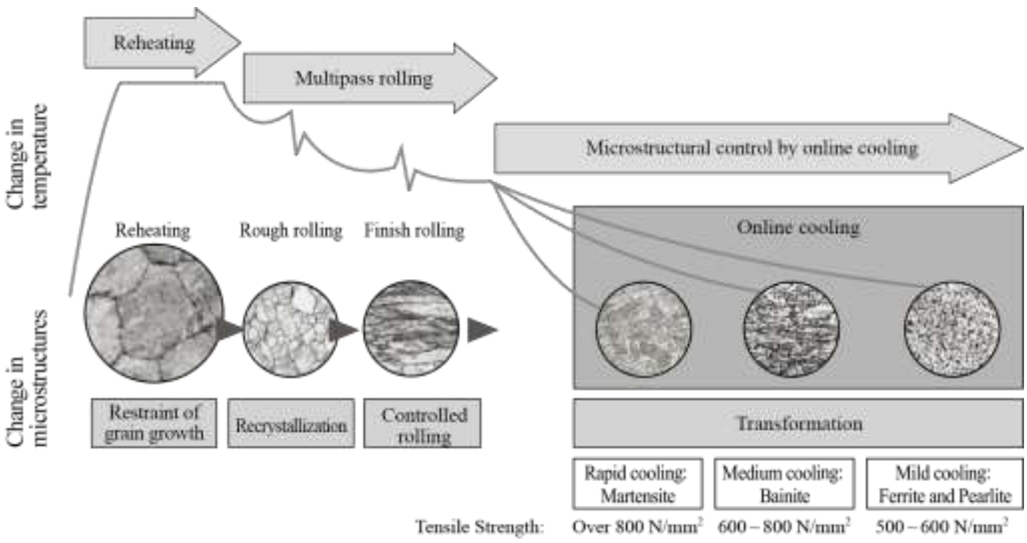

Fig. 8 Outline of the thermomechanical control process (TMCP) [1,2]

Development of production process in Japan has contributed to various high-performance steel plates. One representative key technology is called thermomechanical control process (TMCP). The TMCP can produce steel plates that possess both high strength and high toughness without adding a large amount of expensive alloys. This can be primarily achieved by refining the microstructure through the optimum control of chemical composition, heating, rolling, cooling, and micro alloying elements. Fig. 8 is a schematic image of the TMCP and microstructure control through rolling and cooling [1,2]. With this TMCP, the grain size can be refined from about 20 μm for ordinary steels to around 5 μm, resulting in high strength, ductility, and weldability.

5. Seismic design and seismic-resistant steels

Japan is located in an extremely active seismic area of the world; therefore, it has a long history of battles against the disasters. Fig. 9 shows the timelines of major earthquake events together with observed phenomena, seismic-design methodology, and steel materials for buildings. As seen in this history, Japan has endeavoured to find better ways to protect buildings and infrastructure against earthquakes. Such noteworthy activities include the developments of seismic-design methodology and seismic-resistant steel materials.

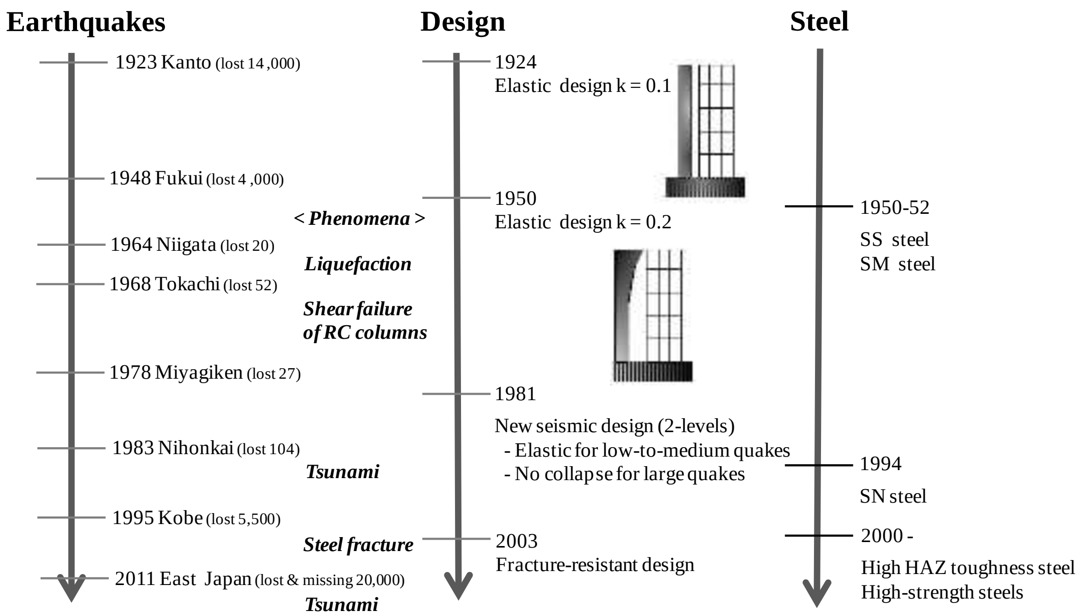

Fig. 9 Timelines of earthquake events, design methodology, and steel material

Considering the inherent uncertainty of earthquakes, the seismic design of buildings underwent a significant change in 1981 from elastic design to inelastic design. In response to this change, new seismic-resistant steels for buildings, such as SN steel specified in JIS G3136 (steel with TS = 400 N/mm^2 and yield strength (YS) = 235 N/mm^2; steel with TS = 490 N/mm^2 and YS = 325 N/mm^2) and SA440 steel (TS = 590 N/mm^2 and YS = 440 N/mm^2), were developed. These steels effectively contributed to increasing the inelastic deformation capacity of members and frames. Among other requirements, those such as 1) upper limit of yield ratio (YR) (ratio of YS to TS) and 2) variation range limitation (upper and lower limits) of YS, are special properties that must be satisfied for the steels.

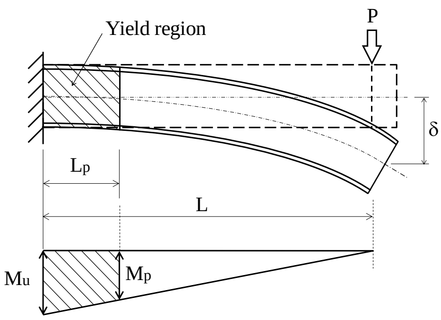

Fig. 10 Yield spreading [1,2]

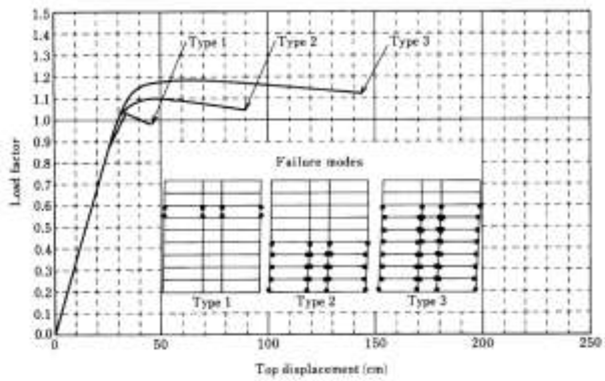

Fig. 11 Collapse mechanisms and their effects [4]

The YR is an index that is directly related to the inelastic deformation capacity of steel members. As seen in a simple cantilever beam under a moment gradient (Fig. 10) [1,2], which is a partial model in a moment resisting frame subjected to seismic force, the yield spreading length L_p defined by plastic moment M_p and ultimate strength M_u at the end of the beam is directly related to the YR of the steel. The lower the YR, the larger is the inelastic spreading length L_p, and thus, the larger is the inelastic deformation capacity. Based on this consideration, an upper limit of YR was regulated as 80% for steels with a TS of 400–600 N/mm^2. These steels are produced using microstructure control such that the necessary strength and YR are typically achieved through a two-phase microstructure (hard and soft) and the proper control of the volume fraction, grain size, and strength ratio of each phase.

In contrast, the variation range (between the upper and lower values) of YS is another important index for the deformation capacity of an entire frame. As shown in the push-over analyses of six-storied frames with different beam-to-column strength ratios (Fig. 11) [4], the Type 3 collapse mechanism called “weak beam and strong column mechanism” in which the beams yield prior to the columns can increase the deformation capacity of the entire frame. To ensure this mechanism, inevitable variation in the YS of the steel must be limited and controlled; thus, the range between the upper and lower values was limited to less than 120 or 100 N/mm^2 for steels with TS values between 400 and 600 N/mm^2. This range limitation was achieved mainly by precise control of the production process.

Table 1 Comparison of steel specifications for seismic design [1,2]

Country or region	Specification and designation	Yield strength		Maximum yield ratio	Charpy impact test	
		Minimum (N/mm^2)	Maximum (N/mm^2)		Minimum energy (J)	Temperature (°C)
Japan	JIS G3136 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 ratio is required not in the EN-10025 but in Eurocode 3
*2 Supplemental requirements

The limitations on YR and variation range of YS for seismic-design purpose were first introduced in Japan and later adopted in the rest of the world. Table 1 shows a comparison between the major specifications for steels with comparable YSs [1,2]. As shown in the table, Japan’s specifications are stricter than those in other countries in terms of YR, variation range, and fracture toughness. Note that the Eurocode does not specify the limitation on the variation range of YS; therefore, there is room for discussion on seismic-design requirements.

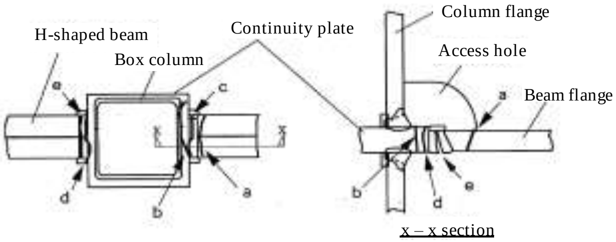

Fig. 12 Fractures at the beam ends [5]

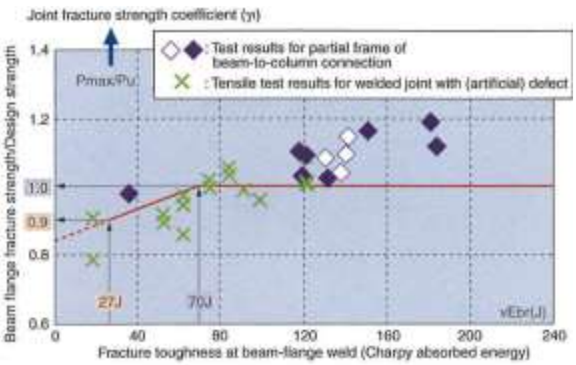

Fig. 13 Toughness requirements [5]

After seismic-resistant steels were introduced in the market, the Kobe Earthquake in 1995, which caused a loss of more than 6000 humans, raised the issue of fractures at beam–column connections in steel frames. Even though the requirement of fracture toughness was already stipulated for the base metal (Table 1), many fractures were observed at the beam–column connections in the steel frames. According to site surveys, the following two major types of fractures were observed at the welds in the lower beam flanges as shown in Fig. 12: one initiated from the toe of the access hole (“a” in Fig. 12) and another from the ends of the beam flange welds (“b” through “e” in Fig. 12) [5]. It was also reported that shop-welding cases tended to have type “a” fractures, whereas on-site welding cases tended to have other types.

An extensive research effort was made in the late 1990s to early 2000s on the fracture behaviour at the beam–column connections. The results of the research suggested that fracture toughness in the weld part was very important and that a Sharpy impact value of at least 70 J was necessary at a temperature of 0 °C as shown in Fig. 13. In general, the value of the toughness at the heat affected zone (HAZ) was the smallest in the weld part; therefore, securing its toughness is an integral part in fracture-resistant design. Generally, the toughness requirement is imposed on the base metal, but research showed that the requirement should be extended to the entire weld parts. Since the HAZ toughness was generally evaluated through time-consuming tests, a toughness estimation formula was proposed based on the chemical composition of steel under limitations of welding heat input and interpass temperature [2].

6. Damage-control system and steels for buckling-restrained braces (BRB)

A new type of seismic-resistant structural system called the damage control system was proposed in the late 1980s. Contrary to the traditional system that absorbs seismic energy through plastification of beams and columns, the new system effectively absorbs seismic energy by added devices (dampers). One of the representative key technologies is buckling restrained braces (BRBs) that have the capability of resisting both compression and tension forces without buckling and other sudden failures. Due to the stable hysteresis behaviour, it is possible to make a building design such that the BRBs can absorb most of the seismic energy while the beams and columns remain intact. A typical BRB comprises a brace member, buckling restraining steel tube, and filling materials (such as cement mortar) in between the brace and the tube, as shown in Fig. 14 [2]. Apart from the BRBs, various devices including types of shear walls were developed and widely used in the Japanese market.

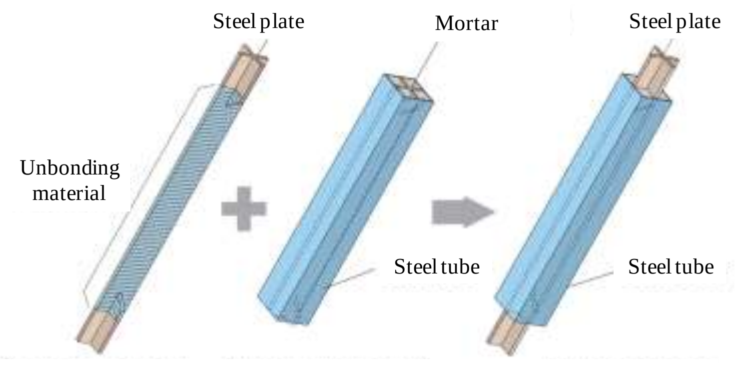

Fig. 14 BRB and its components [2]

As for the steel materials, low-YS steels (100 and 225 N/mm^2) called low yield point (LY) steels were developed (Fig. 15) for the dampers in response to greater needs for accomplishing large and stable energy absorption. LY steels have suitable material characteristics such as large elongation and excellent low-cycle fatigue resistance. They were produced by primarily decreasing content of carbon and other impurities in the steels. On the opposite side of the spectrum, with a wider use of the damage control system, high-strength steels with TS values of 800 N/mm^2 (YS = 630 N/mm^2) and subsequently 1000 N/mm^2 (YS = 880 N/mm^2) were put into use around the year 2010 (Fig. 15). These high-strength steels did not meet the YR requirement stipulated for seismic-resistant steels in Japan but were used because the seismic safety of a building is secured mainly by the dampers. As seen in the above cases, an arrival of a new structural system attracted new steel material developments.

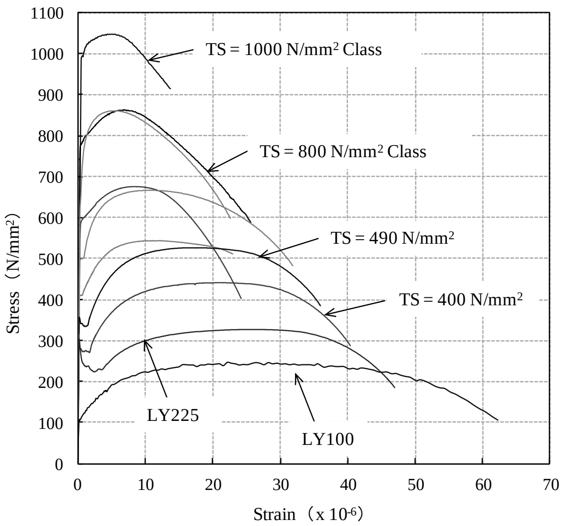

Fig. 15 Stress–strain curves of various steels including very low and high-strength steels

7. Future trends and potential of steel materials

As shown in the previous sections, various high-performance steels have been developed and applied in Japan in response to changes and advances in design methodology, structural systems, or steel production technology. Innovation in Japan was accelerated by various needs caused by rapid economic growth, serious disasters like earthquakes, and so on. Further needs would arrive in the future as an opportunity to challenge more advanced steel structures and materials. Table 2 shows some possible future trends of steel structures, needs for steel materials, and key challenges faced by material innovation. As seen in the table, higher performance steels may play an important role in realizing the future trends of steel structures.

Table 2 Future trends of steel structures and corresponding challenges faced by steel materials

Future trends of steel structures	Needs for materials from structure’s viewpoints	Key challenges to material innovation	
Taller buildings	High strength	Buildings	Steel plates and shapes (over 1,000 N/mm^2): Weldability, inelastic deformation capacity
			High tension bolts (over 1,400 N/mm^2): Hydrogen embrittlement
Longer bridges		Bridges	Steel plates (over 800 N/mm^2): Fatigue resistance (weld & base metal)
			Cable wire （over 2,000 N/mm^2): Material strengthening technologies
Higher seismic safety	High energy absorption	Low-cyclic fatigue (against Mega-quakes)	
Lower life cycle cost	High corrosion resistance	Corrosion resistance for near-coast environment	
	High fire resistance	High temperature resistance over 600ºC	
Higher comfortness	High stiffness and rigidity	Young’s modulus control (higher modulus)	

One may have a question on the potential increase of material performance in the future. Fig. 16 shows the typical range of the TS of major industrial materials [1,2]. The typical TS of steel plates and shapes for construction is between 200 and 600 N/mm^2, but the strength reaches 4,000 N/mm^2 when wires for steel cables and cords (for automotive tires) are included. This indicates steel has a wide range of strength compared with the other materials. This variety is due to the fact that steel is an alloy of iron and carbon and undergoes phase transformations, most importantly, during cooling from high temperatures. By changing the carbon content and cooling rate, it is possible to produce a variety of microstructures, thereby resulting in a wide range of material characteristics. Since the theoretical strength of steel (when no defects exist) exceeds 10,000 N/mm^2 (Fig. 16), it could be said that steel is still a developing industrial material that has a great potential for increasing its strength further.

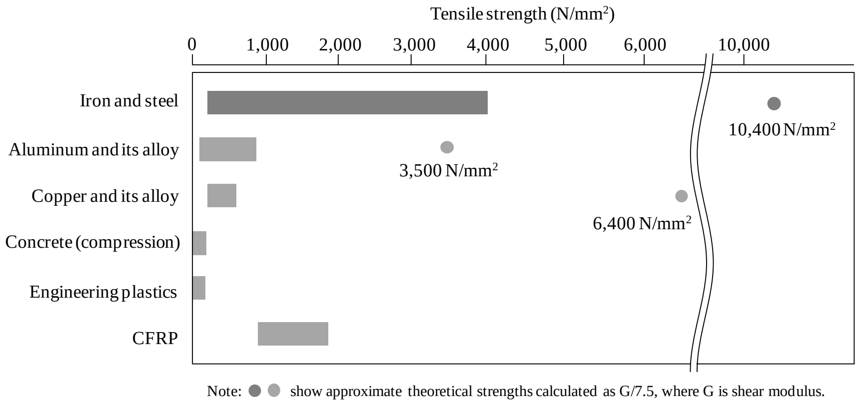

Fig. 16 Strength increase potential of various materials [1,2]

8. Conclusions

This paper reviewed the advances in steel materials and structures in Japan, focusing on steel buildings. It was seen that new design methodologies and structural systems have enabled progress in steel materials, and in turn, an innovation in steel materials has given birth to further advances in steel structures. For steel buildings, new seismic designs have led to seismic-resistant steels, realising high-rise buildings in extremely earthquake-prone regions.

The various types of steels covered in this paper included high-strength steel plates with TS values of 600 to 1,000 N/mm^2, SHTBs with a TS of 1,400 N/mm^2, seismic-resistant steels with an upper limit for YR and a narrow range of YS, and low strength steels for seismic-energy absorption dampers for new structural systems. It was shown through a comparison among various materials that steel materials still have high potential for further improvements in performance, which would contribute to the growing global market.

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