Steels, steel products and steel structures sustaining growth of society (infrastructure field)

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Technical Review

Steels, Steel Products and Steel Structures Sustaining Growth of Society (Infrastructure Field)

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1. Introduction

In this technical review, public facilities that support the safety, security and progress of society and private facilities, including buildings, are collectively called "infrastructure." There are many types of infrastructure—roads, railways, rivers, ports, flood control afforestation, erosion control, architecture, housing, and electric power. Specific structures (hardware) that constitute infrastructure include bridges, foundations, revetments, embankments, tunnels, buildings, houses, and works, etc. Because of its diversity, infrastructure is required to have various functions and performances.

As exemplified by the Great East Japan Earthquake that caused unprecedented property damage and loss of life, it is of paramount importance that infrastructure incorporates a function for shelter from such natural disasters as earthquakes and typhoons; that is, a function to maintain the safety and security of society. On the other hand, infrastructure, which is a result of economic activity, is also a fixed asset accounting for part of the social expenditure. Therefore, it is constantly exposed to severe demands for cost cutting. In view of the rapidly changing society and economy, there may well be demands that such infrastructure be completed in a comparatively short time. Nevertheless, once completed, the infrastructure is expected to function for a long time. Demands to meet complicated conditions are a prerequisite for infrastructure. That is why energetic R&D into infrastructure has been carried out for many years.

As demonstrated by, for example, the world's first iron bridge constructed in 1779, or the obsolete foghorn post of the signal cabin (constructed in 1910)[1] at Inubozaki, made from steel manufactured at the former Yawata Steel works, iron and steel have long been among the fundamental materials used for infrastructure. It is no exaggeration to say that much of the progress in infrastructure that has been made so far is attributable to steel materials. The performance of steel materials, on the other hand, has been improved to help promote the development of infrastructure. Out of the global steel consumption of about 1,300 million tons, 45% is for construction. The use of steel materials for construction is estimated to exceed 50% in China and top 60% in India, Mexico and Indonesia, respectively. In the future, it is expected that demand for steel materials in the field of infrastructure will continue to increase and that uses for steel materials will become increasingly diverse.

In this technical review, with the focus on steel products and building materials for infrastructure and on technology for their application, we review the change in market needs over the past forty to fifty years, including the changes in market climate and conditions, and describe activities to develop new technologies at Nippon Steel Corporation. In addition, on the basis of the ongoing changes in the infrastructural environment, we look to the future of technology in this particular field.

2. Changes in Environment and Needs in the Field of Infrastructure

2.1 Changes in the field of infrastructure and Nippon Steel's products and technologies

Fig. 1 shows examples of major events, structures, natural disasters and accidents, codes/standards and Nippon Steel's new products and new technologies, all having had a significant influence on Japanese society and the economy in the past. In infrastructure expansion and improvement, the National Comprehensive Development Project, the Tokyo Olympics, the Osaka International Exposition, etc. were major driving forces. As shown, huge infrastructures, including the Shinkansen (bullet train), expressways, long bridges and tunnels, have been constructed since the 1960s. In that process, improvements have been made to conventional design methodologies, such as the application of plastic design in place of elastic design. On the other hand, the newly enacted environmental laws, including the Noise Regulation Law and the Vibration Regulation Law, strongly called for giving due consideration to the environment during construction of infrastructures. By around 1970, Nippon Steel established an organization to supply sheet piles, steel pipe piles, light rolled sections, wide flange beams, and cold-rolled box columns, etc. to meet the brisk demand for steel materials for the development of infrastructure. Since the 1980s, the company has developed and introduced to the market diverse building materials and related technologies in a timely response to the enactment of new laws or changes in design methods (Fig. 1).

2.2 Changes that influenced infrastructure and activities of Nippon Steel

The changes in environmental conditions and technological needs in the field of infrastructure can be analyzed from the following three viewpoints.

(1) Changes in environmental conditions accompanying social growth (germination → growth → maturity)

The development process of Japanese society can roughly be

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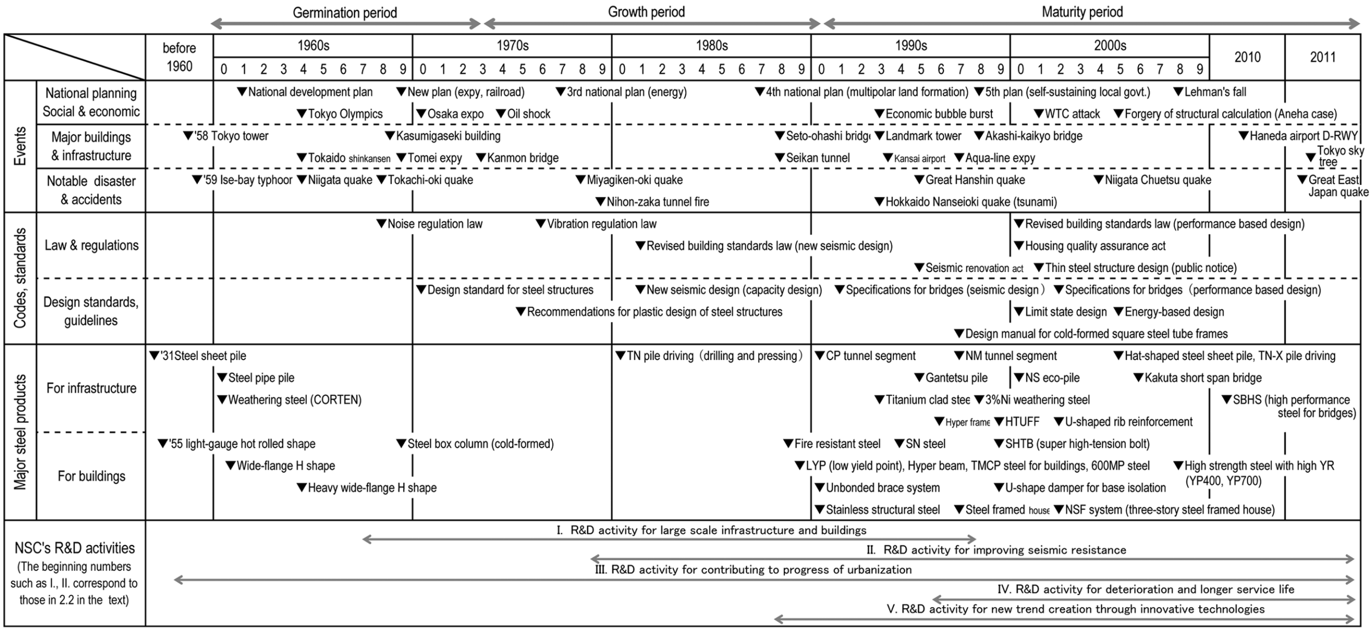


Fig. 1 History of events, codes and standards, and steel products related to infrastructure

divided into a period of germination until around 1973, a period of growth until around 1990, and a period of maturity up until the present. During the process of growth, not only did the environmental conditions change, but so too did the infrastructural requirements. In the germination period, large-scale infrastructures need to be developed within a short time; in the growth period, with the progress of urbanization, infrastructure needs to be developed in harmony with the city environment (e.g., use of lighter building materials and low-noise, low-vibration work executed in confined spaces); and in the mature period, with the ripening of the economy, reductions in construction costs are called for, and demands to minimize life cycle costs, and save energy, etc. become more conspicuous, and accordingly, new materials that are less expensive and more durable and that help save labor are sought.

(2) Changes in required performance induced by earthquakes, typhoons and other natural disasters/accidents

Some changes have nothing to do with the growth of society. Upgrading performance requirements to a more exacting standard in the wake of a large-scale disaster is an example. When the safety/security target changes markedly, the codes/standards applied to determine the infrastructure specifications are revised, calling for changes in seismic performance, fire-resistance performance, resistance to landslides, etc. which are required of infrastructure. There are cases in which the performance requirements of infrastructure change remarkably as a result of improved accuracy in risk assessment thanks to progress in science and technology or as a result of a change in the framework for design methods on a global basis. For example, in the new performance-based design method in which more than one performance target is set for each level of damage to a structure, technology to control damage is required.

(3) Changes in the market brought about by innovative steel technology

Not all needs are driven by the market. Sometimes innovative techniques and new business models, or innovations, can bring about a change in the market, thereby giving birth to new needs. Although this is considered rather unlikely to happen in the field of infrastructure, innovations in steel materials or structures have brought about a new market or a new need. Fire-resistant steels, unbonded braces and steel-framed houses are among typical examples. The development of fire-resistant steel overturned the established theory that structural steel offered poor fire resistance. The advent of fire-resistant steel led to the birth of a market for steel building frames without fire-resistant covering. The practical application of unbonded braces has made it possible to spread the damage-controlled structure, in which the damage caused during an earthquake is confined to certain structural members, and the development of steel-framed houses has dramatically expanded the use of steel sheets around 1 mm in thickness. Nippon Steel has continued to develop new products and new technologies adapted to the changes in environmental conditions and market needs. The company's activities in the field of infrastructure can be summarized as follows.

I. Activities to realize a large-scale infrastructure that supports the growth of society
II. Activities to enhance the seismic performance of infrastructure in Japan—an earthquake-ridden country
III. Activities adapted to the progress of urbanization and the need for environmental conservation
IV. Activities to check the deterioration of infrastructure and prolong the life of infrastructure
V. Activities to set new trends through innovations.

We describe Activities I through IV in Section 3, and Activity V in Section 4.

3. Activities Adapted to Changes in Market Conditions and Needs

3.1 Activities to realize large-scale infrastructure in support of society's growth

Constructing a long-span bridge is a typical example of a huge project. In the construction of long-span bridges, therefore, most advanced steel materials and technologies have been employed. **Fig.**

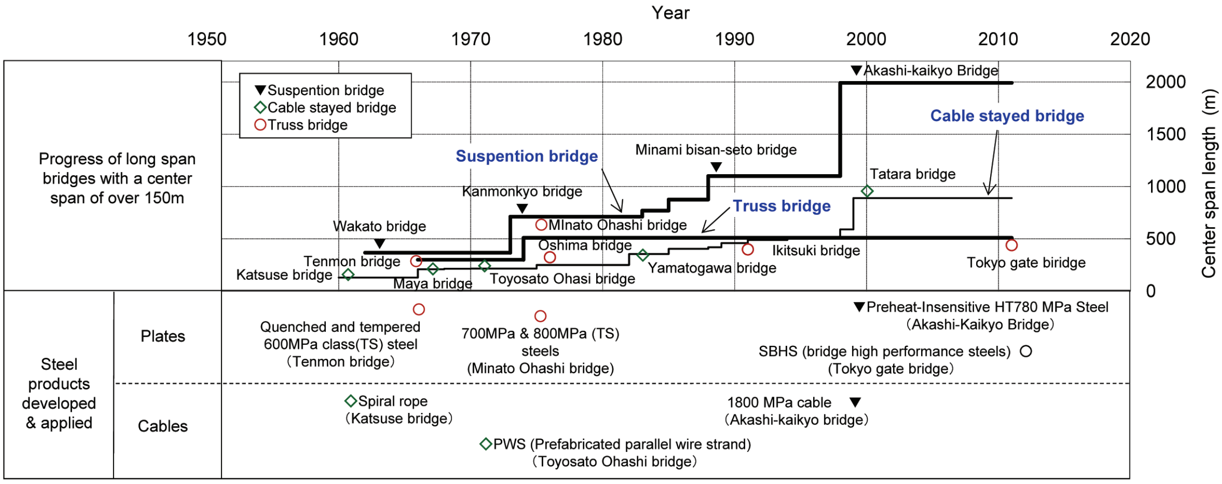


Fig. 2 History of maximum bridge span and related steels

2 shows the change in maximum span of suspension bridges, cable-stayed bridges and truss bridges in Japan. As shown, the maximum spans of suspension, cable-stayed and truss bridges have continually been expanded. At present, the maximum span is roughly 2,000 m for suspension bridges, 900 m for cable-stayed bridges and 500 m for truss bridges.[2,3] It is steel materials that have allowed for such long spans. Nippon Steel has developed and marketed high-performance steel materials for long-span bridges (see the bottom column in Fig. 2).

Looking at cables for suspension bridges, steel in the 1,550-MPa class was employed for the George Washington Bridge in the 1930s. For the Akashikaikyo Ohashi Bridge, steel cabling in the 1,800-MPa class was developed. A cable of this type was also applied to the Kurushimakaikyo Ohashi Bridge that was built later. For cable-stayed bridges, spiral ropes of stranded wires (for the Katsuse Bridge) and locked coil ropes were used in the 1960s. For the Toyota Ohashi Bridge and other long-span bridges constructed later, cables of parallel wire strands having higher tensile strength and larger elasticity modulus were developed.[3,4]

Concerning steel plates, a tempered steel plate of 600-MPa class was applied to the Tenmon Bridge, Japan's largest truss bridge at the time of completion. After that, large quantities of steel plates of 700/800-MPa class were adopted for the Minato Ohashi Bridge. However, the fabrication of those steel plates proved problematic, such as the high preheating temperature. For the Akashikaikyo Ohashi Bridge, therefore, a steel plate of 800-MPa class preheated at a lower temperature was developed.[5] Thereafter, attempts were made to cut overall costs by further enhancing the fabrication of the above high-strength steel plate. As a result, a high-performance steel, SBHS, for bridges was developed.[6,7] The strength of steel in a plate-girder bridge is determined by its fatigue and deflection. There are two grades of SBHS—one has a yield strength of 500 MPa, the marginal strength free from the above limitation, and the other is of 700-MPa class suitable for suspension and cable-stayed bridges.

In order to impart both high strength and good weldability to SBHS, the thermo-mechanical control process (TMCP) was applied to restrain the addition of alloys and lower the preheating temperature or eliminate the need to preheat for welding. It has been reported that the cost of constructing the Tokyo Gate Bridge,[6] in which 500-MPa SBHS steel was used in large quantities for the first time, could be reduced by as much as twelve percent. SBHS has been specified in JIS and is being posted in design standards for road bridges.

In the field of architecture too, with the increase in building height and span, more and more high-strength steels have been applied. For Tokyo Sky Tree® (**Fig. 3**), which is the world's tallest freestanding radio tower (634 m) scheduled to be completed in 2012, the 780-MPa steel and other high-performance steels that have lesser amounts of alloying elements added to cut costs are abundantly used.[8] In addition, a seamless flux-cored wire without caulked parts (SF-55 of Nippon Steel & Sumikin Welding Co., Ltd.) has been adopted as a welding material. Through its high deposition efficiency, low preheating temperature (low hydrogen concentration), etc., SF-55 helps enhance the efficiency of welding of high-performance steels and ensure the prescribed quality of welds. On the other hand, the super-high tension bolt SHTB® (1,400-MPa class)[9] for jointing large-section members, mainly those of high-rise buildings, has been put to practical use, contributing to the strengthening of steel joints.

Fig. 3 Tokyo Sky Tree® (Owner: Tobu Railway Co. and Tobu Tower Sky Tree Co.)

3.2 Activities to enhance the seismic performance of structures in Japan—an earthquake-ridden country

In the past, the performance required of steel materials has been revised each time that significant damage was caused by an earthquake or major improvements in seismic technology were made. The most important change was brought by the New Seismic Design Code for Buildings introduced in 1981. In this method, the concept of plastic design was added to conventional elastic design. As a result, it became necessary for structures and their members to have not only the prescribed strength, but also the prescribed deformability after plasticization. Following the report that brittle factures of welds had occurred in the Great Hanshin-Awaji Earthquake of 1995, even more rigorous performance requirements relating to fracture resistance were added. Thus, the performance requirements of steel materials have changed in emphasis from strength to deformability to fracture resistance. Described below are Nippon Steel's pioneering activities in response to the above changes.

(1) Pursuit of higher material strength and higher member strength (large section)

Amid the trends toward taller buildings and higher seismic performance, Nippon Steel has been pursuing steel materials of greater strength and steel members with higher yield strength (for larger sections). Representative high-strength steel materials include BT-HT440,[10] whose tensile strength is 590 MPa, and BT-HT630,[11] which has a higher tensile strength of 780 MPa. These steel materials were adopted for the Yokohama Landmark Tower and Kokura Station Building. Recently, the company has developed H-SA700,[12] which has 700-MPa class yield strength, and a high-strength yield ratio (YR) relaxation-type steel that features high productivity and low cost.[13] As examples of steel members having large sections, there are the extra-thick H-Shape (HSGH®)[14] and large Hyper-Beam®.[15] HSGH® has mainly been used in foreign countries. It was adopted for Taipei 101 (China, 2004) and Burj Khalifa (UAE, 2007), amongst others. The company's advanced molding technology has made it possible to manufacture extra-thick H shapes having outer dimensions up to 580 mm × 471 mm, with the maximum web thickness and maximum flange thickness being 95 mm and 130 mm, respectively. The wide-flange beam (H beam) having fixed outer dimensions (Hyper-Beam®) that was developed as an alternative to a welded H-beam is also now available in larger sizes. It is now possible to manufacture Hyper-Beams with a beam depth up to 1,000 mm. The Hyper-Beam has a large beam depth and permits reducing the web thickness and increasing the flange thickness and width and hence, it helps bring about an economical design.

(2) Pursuit of higher plastic deformability of steel members and frameworks

Nippon Steel has carried out two pioneering activities to enhance the plastic deformability of its steel products. One was research on enhancing the deformability of a steel member by lowering the yield ratio of the steel material. Yield ratio (YR) is the ratio of yield strength to tensile strength. After introduction of the New Seismic Design Code for Buildings in 1981, the company was quick to begin research on the yield ratio of steel materials and the deformability of steel members. As a result, it showed that lowering the yield ratio of the steel material improved the plastic deformability of the steel member markedly.[16] Thanks to the above pioneering research, the yield ratio has come to be positioned as one of the performance indicators for steel materials for seismic structures. The other was an activity to enhance the deformability of the entire framework of a steel structure. This was research focused on the variance of the yield point (YP) of steel materials.[17] As a means of enhancing the deformability of a steel framework, there is a design technique that engenders a total collapse mechanism of the beam yield type. The underlying concept is that the beams are made to yield before the columns so as to increase the number of plastic hinges in the framework and thereby disperse the damage over the entire framework (**Fig. 4**). With the aid of a probabilistic method, the company demonstrated that the deformability of the entire framework could be improved by reducing the variance of the yield point (narrowing down the margin of YP)[17]. That was the finding that reducing the variance of the yield strength would increase the possibility of the beams yielding before the columns.

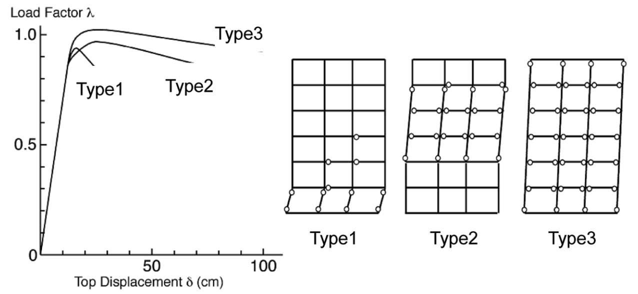


Fig. 4 Relationship between frame collapse modes and in elastic deformation capability

The above research results into the yield ratio and the variance of the yield point were reflected on rolled steels for building frames (SN Steels; JIS G 3136-1994) that were subsequently standardized. The standard provides for upper limits of yield ratio, and upper and lower limits of yield points, etc. as matters relating to the mechanical properties of steel materials, which contribute to the improved seismic performance of building frames. It should be noted that the provisions concerning yield ratios have been introduced in the United States, Europe and China, providing an example of Nippon Steel's activities being globalized.

(3) Pursuit of fracture resistance to prevent brittle fractures

In the wake of the brittle fractures that affected steel structures during the Great Hanshin-Awaji Earthquake, Nippon Steel played a leading role in carrying out a national project to investigate the causes of brittle fractures and establish technology to prevent them. In that project, the company clarified that the brittle fractures of welds at the beam ends were influenced by the fracture toughness and yield ratio of the steel material and by details of the joints. At the same time, the company presented specific conditions and a design flow to prevent brittle fractures, taking into consideration the details of the column-beam joints, the presence of welding defects, and the fracture toughness of materials and welds, etc.[18, 19] The results of the national project have been incorporated into the "Guidelines on Prevention of Brittle Fractures of Welded Joints at Beam Ends of Steel Frames,"[20] which have been contributing to the improved reliability of steel-frame structures. In addition, the company has developed HTUFF® Steel,[21] which permits securing a high HAZ (Heat-Affected Zone) toughness even when welding with a large heat input (e.g., electro-slag welding) which tends to cause the material to deteriorate, through refinement of the HAZ structure by effective utilization of precipitates.

Although this is an entirely different approach, Nippon Steel has also developed and commercialized all-bolted building frames

(Hyper-Frame®)[22] that have dispelled concern about fractures. This structure uses high strength bolts for all the connections and joints that are subject to stress concentration and thereby eliminates the need to weld those connections and joints. It obtained general approval from the construction minister in 1997 (for buildings up to five stories).

3.3 Activity to respond to progress of urbanization and demand for environmental protection

3.3.1 Progress in civil engineering structures accompanying urbanization

The advances in civil engineering structures in urban areas can roughly be divided into: progress with pile foundations with an increase in scale and height of structures; progress with retaining walls that serve to separate specific structures from ports and rivers in horizontal expansions of urban areas; and progress with tunnels, shafts and other underground structures in vertical expansions of urban areas. Nippon Steel has supplied steel products and technologies adapted to the progress of those structures.

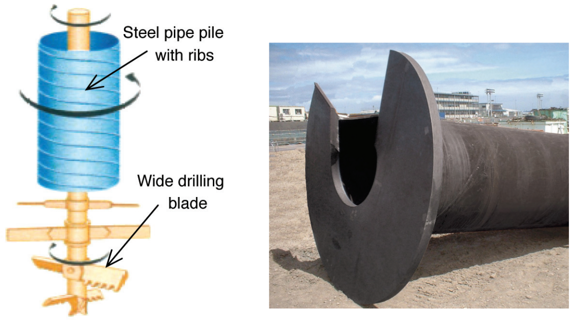
Early pile foundations were mostly pinewood piles and cast-in-place concrete piles.[23] With the increase in the size of structures, steel pipe piles which provide a larger bearing capacity and better work quality were developed. In 1963, JIS standards for steel pipe piles were established, and in 1971, the Japanese Association for Steel Pipe Piles (the present Japanese Association for Steel Pipe Pile/ Steel Sheet Pile Technology) was inaugurated. Nippon Steel has contributed much to the development, practical application and spread of steel pipe piles.

Steel sheet piles have long been used. According to a report, steel sheet piles were used in the construction of the main building for Mitsui as far back as 1903. At first, sheet pile technology was introduced from the United States and Europe. In order to meet the growing need for sheet piles with a higher yield strength, Nippon Steel developed new type of sheet pile known as the "Z-sheet pile" (in 1959). Around 1960, the company created a steel pipe sheet pile with a new construction, allowing for dramatic improvement in cross-sectional characteristics. Thereafter, the company has continually developed new products adapted to increasingly diverse needs.

For urban tunnels, concrete segments had long been the mainstream. With the development of traffic networks in urban areas, branches and sections that are subject to a larger load have increased in number. Accordingly, composite segments of steel and concrete, such as NM and CP Segments,[24, 25] have been developed. In addition, through the development of a continuous underground steel wall made of special structural steel (NS-BOX)[26], etc., the company has responded to the continued increase in size and depth of tunnel shafts.

3.3.2 Response to market needs relating to the environment

In light of growing consciousness about the environment surrounding construction, the government enacted the Noise Regulation Law in 1966 and the Vibration Regulation Law in 1976. Under those conditions, the "low-noise, low-vibration pile embedding method," in which piles are built in a previously excavated hole, was developed to take the place of the conventional method of pile-driving by hammer. At the same time, a new method that does not produce much waste soil was called for. These were the "Gantetsu Pile®" [27] and "NS Eco-Pile®" [28] that were developed to meet the above demands. The Gantetsu Pile® is a composite of a steel pipe pile and soil and cement developed by applying the existing soil improvement technology. It uses a special finned steel pipe to obtain a solid composite unit (**Fig. 5** (a)). The NS Eco-Pile® is a steel pipe pile that has a large-diameter cutter blade at the front end so that it can be rotated and pressed into the ground (Fig. 5 (b)). In order to develop this new pile, the penetrability by rotation and the bearing capacity of various steel pipes were studied in earnest.[28] The NS Eco-Pile® has become widespread as the representative method of building a pile foundation. Producing virtually no waste soil, it is highly evaluated as an environment-friendly method.



(a) GANTETSU pile®　　(b) NS-Eco pile®

Fig. 5 Example of environmentally-conscious steel pipe pile

3.3.3 Response to demand for piles of higher yield strength and reduced cost

Examples of steel pipe piles and steel sheet piles developed in response to the progress of urbanization are described below.

(1) Long, large-section steel pipe pile method to meet need for higher yield strength

In the field of building foundations, the 2001 Revision of the Building Standards Law made it possible for civil engineers to adopt their own bearing capacity equation based on the prescribed loading test, thereby paving the way for practical use of piles with a larger bearing capacity.[29] The "TN-X"[30] method was developed under such conditions. In this method, a large protective foot is formed by injecting cement milk into the ground through a steel pipe while rotating a spreading blade head inserted into it and mixing the cement milk with the soil (**Fig. 6**). The maximum diameter is 1,400 mm for the pile and 2,400 mm for the protective foot. In a bearing stratum whose N-value is 60 or more, a system of steel pipe piles can manifest a pile-end bearing capacity of up to 17,900 kN. This method can be applied even to long steel pipe piles driven 70 to 75 m deep into the ground. It is also applicable to high-strength steel pipes (NSPP 520).

(2) New steel sheet piles enabled cost reductions

Formerly, steel sheet piles were mostly 400 mm in width. Since

Fig. 6 Enlarged pile tip reinforcement of TN-X pile (2,400mm ϕ)[28]

Fig. 7 Configuration of hat-shaped steel sheet pile

Fig. 8 Hat-shaped steel sheet pile with pile tip enclosure

1997, when an action plan concerning measures to cut the cost of public works was formulated, it has become an urgent necessity to cut construction costs. Under that condition, Nippon Steel developed a 600-mm-wide steel sheet pile,[31] as well as a 900-mm-wide hat-type sectioned steel sheet pile.[32] The development of such wider sheet piles has made it possible to reduce the number of sheet piles required and shorten the construction period.

At present, two hat-type sectioned sheet piles are available: 10H and 25H. As a single unit, Type 25H is among the world's largest steel sheet piles. In addition to the large width, the salient characteristics of the hat-type sectioned sheet piles are that the shape has been optimized from the standpoint of cross-sectional performance and impact resistance and that the joints have been shifted to the outermost edges (**Fig. 7**) so as to prevent shear displacement at joints found with conventional sheet piles, and to further enhance the cross-sectional performance. As a result, compared with conventional steel sheet piles (II_w, III_w), the hat-type sectioned steel sheet pile (10H, 25H) has higher cross-section performance while ensuring good drivability.[31]

Nippon Steel has also been developing steel sheet piles for new uses. Ordinary steel sheet piles are resistant to horizontal forces from soil and water pressure, etc. The company has developed a new steel sheet pile that is resistant to vertical forces as well. Thus, it has proposed a steel sheet pile foundation that serves not only as a retaining wall but also as a foundation.[33] Namely, a pair of hat-type sectioned sheet piles are fitted together at the end to form a closed section (**Fig. 8**), thereby making it possible to use steel sheet piles for foundations as well. The closed section at the end of the newly developed steel sheet pile has an end-bearing capacity comparable to that of a steel pipe pile.

3.4 Activities to check the deterioration of infrastructure and prolong the life of infrastructure

3.4.1 Improving fatigue resistance by controlling residual stress

The problem of fatigue in steel structures has become especially conspicuous with heavily operated railways and heavy-duty road bridges. Accordingly, stringent maintenance and management, including periodic inspections and checking for cracks, are required of those steel structures. A number of bridge collapses and suchlike caused by fatigue cracking have been reported abroad. In Japan, too, fatigue failures in road signposts and lampposts, etc. have made the news. Fatigue cracking is caused by welding defects or high stress concentration at the surface of a weld or tensile residual stress comparable to the yield strength of the weld. Here, we describe Nippon Steel's activities to improve the fatigue resistance of steel structures with a focus on reducing the tensile residual stress of the weld.

Fig. 9 U-shaped rib stiffening pole

It is the "U-ribbed structure"[34] that offers good fatigue performance thanks to a low stress concentration and a small tensile residual stress achieved by improving the details of the joints (**Fig. 9**). This structure was proposed by Nippon Steel as an alternative to the triangular rib enforcement for the bases of lampposts and road signposts, etc. The salient characteristic of this structure is that in addition to a reduction in stress concentration by the U-ribbed reinforcement, the tensile residual stress of the weld is significantly reduced as the steel pipe thermal deformation after rib welding introduces a compressive stress around the part subject to stress concentration. It has been reported that thanks to the combined effect of relieving stress concentration and reducing tensile residual stress, the U-ribbed structure is a very effective way to improve the fatigue life of a steel structure. It has already been employed on many lampposts along expressways.

There is a technology to enhance the fatigue performance of welds by peening — that is hammering the welds using a special tool. This is "*Esonix*® UIT" (Ultrasonic Impact Technology) developed by an engineer of the former Soviet Union in 1970. The UIT is mounted with a striker pin at the front end that impacts the weld as it vibrates at high speed. Nippon Steel conducted basic research into UIT, including an attempt to clarify the mechanisms of UIT, and research on the application of UIT to actual steel structures. As a result, it has been clarified that the effect of UIT owes to multiple factors, such as the introduction of a compressive residual stress by the impact of the striker pin, the relieving of stress concentration by improving the shape of the weld, and refinement of the weld's surface structure.[35] With out-of-plane gusset joints, etc., the application of UIT has promoted their JSSC fatigue grade up about two ranks, from D to B. The technology has been increasingly applied to crane runway girders and bridges.[36]

3.4.2 Activities to prevent corrosion of offshore structures by using high-performance steels

In recent years, large projects in marine locations need to remain

Fig. 10 Stainless steel cladding protection (Haneda Airport D-runway)

corrosion-free for 100 years or more. Under that condition, Nippon Steel has developed long-term anticorrosion technology using titanium, stainless steel and other high-performance materials.[37, 38]

Titanium has excellent corrosion resistance. However, since titanium is expensive and cannot be welded with iron, the application of this material for corrosion prevention had been limited. Around 1990, Nippon Steel developed an inexpensive titanium-clad steel product and an economical titanium welding method, which were applied for the first time in the world to the steel bridge piers of the Tokyo Wan Aqualine Expressway (Trans-Tokyo bay bridges and tunnel) in the splash and tidal zones. After that, the titanium-clad steel was also employed for the lower part of the Monbetsu Ryukai Observation Tower, and the floating structure of the Yumemai Ohashi Bridge, etc. The problem of welding the titanium-clad steel plate (1 mm titanium cladding on 4 mm steel plate) to the bridge pier was solved by welding the steel part of the plate to the steel member of the bridge pier.

"Stainless steels" are second only to titanium in corrosion resistance. They had been considered as promising corrosion-resistant materials applicable to steel structures. However, conventional stainless steels, such as SUS 316L, were subject to pitting and crevice corrosion in environments without cathodic protection against sea corrosion. Therefore, new materials with better corrosion resistance were required. With an eye on its NSSC270 (20Cr-18Ni-6Mo) steel that had been put to practical use in seawater desalination plants, etc., Nippon Steel proposed a new anticorrosive coating method for the jackets in the splash and tidal zones in the Haneda Airport Re-expansion Project. The proposal was accepted and the new method was put into practice (**Fig. 10**). In order to implement the method, in which the steel pipe is covered with a thin sheet of stainless steel about 0.4 mm thick, the company developed a new indirect seam welding method, which has helped cut the cost of covering significantly. In addition, in the above project, the company proposed a new anticorrosion method in which the steel girders of the runway should be covered with a thin panel of titanium. This proposal was also adopted.[39)]

3.4.3 Weathering steels in corrosive atmospheres and their application technology

As steel materials which do not require anticorrosion painting, weathering steels have been widely used. However, the conventional JIS weathering steels (SMA steels) can only be used effectively when the airborne salt concentration is within a certain limit or in areas a minimum distance away from the coast. On the other hand, in coastal areas, the need to construct bridges using weathering steels has remained strong and techniques to predict the long-term durability of weathering steels taking into account the local environment have been called for. Under those conditions, Nippon Steel has developed new weathering steels and new techniques to evaluate their durability.

In the case of JIS weathering steels (containing Cu, Ni and Cr), the reaction (at the steel surface) of chlorine ions (Cl^-) in the rust layer impairs their durability. The "Ni-based weathering steel"[40] was developed based on the knowledge that the above reaction of Cl^- ions is restrained in weathering steel whose Ni concentration exceeds a certain level. In a simulated exposure test carried out in a coastal area exceeding 0.05 mdd too, the developed steel proved to have good resistance to salt damage. Two types of Ni-based weathering steel have been developed—1%Ni and 3%Ni—so that the better type can be selected according to the actual environment.

Macroscopically, the applicability of weathering steels has been judged based on the concentration of airborne salt and the distance from the nearest coast. However, judging the applicability of specific weathering steel has become increasingly difficult, calling for microscopic and quantitative information. The technology that Nippon Steel developed to meet this need is software ("YOSOKU®") to predict the decrease in steel plate thickness by corrosion that takes into account all the environmental factors, such as the temperature, humidity, sulfur oxide concentration, and wind velocity.[41, 42] This has enabled more rational judgment on the applicability of weathering steels. In addition, the company has developed a "patch test method," which permits quantifying the durability of steel easily, and various application techniques,[42] including a rust-stabilizing paint that restrains the initial rust from dropping.

4. Setting New Trends through Innovation

4.1 Challenging the common belief that structural steels have poor resistance to fires

Until the advent of fire-resistant steels (around the 1980s), the great majority of steel-framed buildings were required, almost without exception, to meet the specifications for fire-resistant structures (mean steel temperature not higher than 350℃ and maximum steel temperature not higher than 450℃) provided for by the Building Standards Law of Japan. In those days, it was considered common sense to cover a steel frame with a fireproofing material with good heat insulation. Therefore, the image of "steel-framed buildings having poor resistance to fires" was quite prevalent. On the other hand, a number of problems involved in applying a fireproofing material had already been pointed out, including the poor working environment, extended period of construction, and reduced freedom of architectural design. Under those conditions, technology to dispense with the need for a fireproofing material was much sought after. In 1988, Nippon Steel came up with a "fire-resistant steel" having excellent high-temperature properties,[43] and succeeded in putting it to practical use for the first time in the world. The salient characteristic of the fire-resistant steel was that it was the world's first structural steel that guaranteed a yield strength equivalent to two thirds or more of the normal-temperature F-value (design material strength) at the prescribed high temperature, in this case 600℃.

Fig. 11 shows the high-temperature strength properties of the fire-resistant steel, SM50A-NFR (present NSFR490A)[44]. It can be seen from Fig. 11 that the fire-resistant SM50A-NFR steel has greater high-temperature strength than the steel material for ordinary welded structures, SM50A (present SM490A), and that its yield point (YP) at 600℃ is equivalent to at least two thirds of the design material strength (22 kgf/mm^2, 216 MPa) at ambient temperatures. By

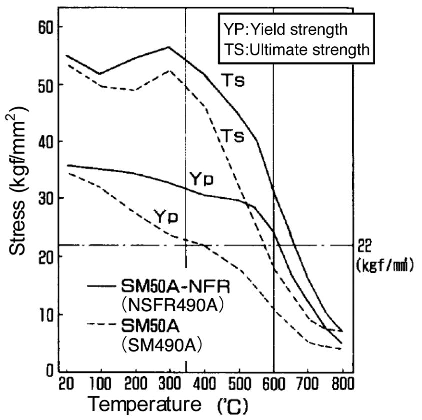


Fig. 11 Mechanical properties at elevated temperatures of fire-resistant steel and ordinary steel (SM)[41]

(a) Outdoor parking lot **(b) Atrium building**

Fig. 12 Applications of fire resistant steel

guaranteeing such high-temperature strength properties, Nippon Steel succeeded in creating a new market for "steel-framed buildings without fireproof covering," including, for example, drive-in parking facilities (**Fig. 12** (a)) and atriums (Fig. 12 (b)) which are free from flashover fires. In addition, the application of fire-resistant steel has made it possible to omit the covering work, shorten the construction period and design neat steel frames without fireproof covering (Fig. 12).

In 1989, Nippon Steel issued guidelines on the fire-resistant design of buildings using fire-resistant steels and established a new method of verifying fire resistance beyond the criteria of the Building Standards Law of Japan. The above guidelines were the forerunner of performance-based design methods in the field of fire engineering. In 1990, Nippon Steel disclosed its fire-resistance technology to the other integrated iron and steel manufacturers, paving the way for the spread of fire-resistant steels. The development of fire-resistant steels is an example of pioneering, innovative and foresighted development of building materials that not only allowed for steel-framed buildings without fireproof covering, but also created a new trend toward the development of performance-based fire-resistant methodology. It also leads the current trends in the development of building materials—reduction of CO_2 emissions and improved recyclability of steel frame members by minimizing the application of fireproof covering.

4.2 Development of buckle-free braces and damage-controlled structures

Braced structures are one type of rational construction. However, a brace is subject to buckling under a compressive force. If the brace

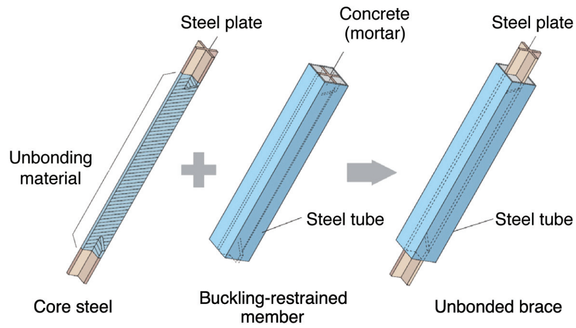


Fig. 13 Outline of unbonded brace

buckles, its yield strength and energy-absorbing capacity decline markedly. When a cyclic force (e.g., a seismic force) is applied to the brace, plasticization under tension and buckling under compression occur alternately. As a result, the hysteretic behavior of the brace becomes extremely complex. Therefore, it was common sense in structural design that "compression resistance is not expected of braces." But the unbonded brace challenged that notion.[45] Nippon Steel worked out a mechanism for restraining the buckling—a drawback—of braces. The mechanism was first put to practical use in 1986. The unbonded brace consists of a plane or cruciform section steel plate constrained by a steel tube and concrete via unbonded material (e.g., asphalt) (**Fig. 13**). This forms a bracing member whose buckling is effectively restrained.

The unbonded brace was applied as a damage-controlling member of a damage-controlled structure that was proposed at the same time that the unbonded brace was developed. This set a major trend toward seismic-resistant buildings. The damage-controlled structure allows for improved seismic performance and continued use of the building by replacing the damage-controlling member that absorbs the seismic energy in a concentrated manner. In view of the spread of damage-controlled structures, Nippon Steel developed a new low-yield-point steel, "BT-LYP®," to enhance the performance of unbonded braces.[46-48] It has been demonstrated that unbonded braces using the LYP steel have a stable hysteretic characteristic and a good low-cycle fatigue characteristic. They have been widely used in Japan and abroad. In the United States, they are specified in the Standards of the American Institute of Steel Construction (AISC) and the number of hospitals and other public buildings that are applying them is increasing.

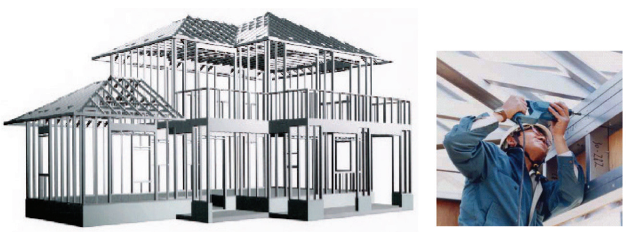
4.3 Steel houses that can even be built by carpenters, and proposals on "shapes"

The history of steel houses in Japan dates back more than half a century. Steel houses are typically light-gauge, steel-framed constructions which now account for 10% to 20% of all new houses. A light-gauge, steel-framed house is built by connecting 2.3-mm or thicker steel sections together by means of welding or bolting. Ordinarily, it is subjected to the electro-deposition process to ensure the required durability. Since building light-gauge, steel-framed houses requires large-scale equipment and high levels of skills, they are generally built at an integrated plant. The above restriction has prevented them from becoming more popular, and accounts, at least in part, for their modest share of the market despite their long history.

Our "Steel House" activity was started with the aim of breaking out of such a situation.[49] Under the Urban Steel Society (sponsored by the present Ministry of Economy, Trade and Industry), Nippon Steel took the initiative in launching research on steel houses in 1994. Steel house (**Fig. 14**) constructions were popular in the United States and Australia in those days. They were so-called two-by-four steel houses fabricated by joining together galvanized steel shapes about 1.0 mm thick using self-drilling tapping screws. The steel shapes used are so thin that they can be cut with a circular saw and screw-jointed with an impact screwdriver. Unlike conventional steel-framed houses, the two-by-four steel house requires no special skills, and can even be built by carpenters.

Although the two-by-four steel house was expected to open a new market, there were a number of legal and technical problems and limitations that had to be cleared before it could be put to practical use in Japan. Nippon Steel played the leading role in promoting the establishment of standards and criteria relating to design, construction and durability of steel houses. In 2001, the company succeeded in having an official design code of steel houses. As a result, it became possible to use galvanized shapes 0.4 to 2.3 mm thick as structural materials, and two-by-four steel houses came to be recognized as comparable to wooden houses and traditional light-gauge steel-framed houses. Today, steel houses that have secured official fireproof certification are applied to company houses and bachelor dormitories, etc. of up to three stories.[50]

The two-by-four steel house also prompted the utilization of steel sheet members in Japan. As the thickness of the steel material is reduced, it becomes easier to obtain steel members of various cross-sectional shapes by cold roll forming. On the other hand, this can lead to a complex form of buckling of the member accompanied by twisting or local deformation. Therefore, Nippon Steel has conducted research on design methodology paying special attention to the buckling of thin steel members and optimization of cross-sectional shapes by taking advantage of the freedom of form.[51] **Fig. 15** shows an example of replacing a wooden member with a steel sheet member. As shown, it has become possible for the company to propose various cross-sectional "shapes," starting from C-shaped through Σ -, Ω - and J-shaped, and so on.[52] Incidentally, the technology developed here is utilized as "Katachi Solution®" to reduce weight and increase rigidity in home appliance cabinets, etc. (see Chapter 1, 1-3).



(a) Skelton **(b) Self-drilling connection**

Fig. 14 Outline of steel-framed house

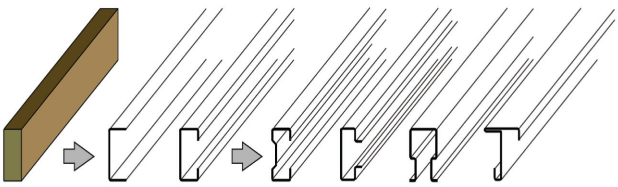


Fig. 15 Light-gauge steel shapes as substitutes to wooden member

5. Outlook for Future Technologies

5.1 Steel materials to secure greater safety against disasters/accidents

One of the lessons many have learned from the recent Great East Japan Earthquake is probably the most rudimentary question as to the possibility of accurately estimating the scale of a natural disaster. After all, any prediction technique that depends on a limited amount of data accumulated over decades or so has its own limits. Thus, it is necessary that the infrastructure should be equipped with as much resistance to external forces as possible and that it should be easily repairable if damaged. The direction of technological development for that purpose is considered to utilize the "redundancy" of structures and implement "stratification"[53] of structures, whereby the structures are classified according to their role as in skeleton infill.

Utilizing redundancy means making a structure that does not collapse even if a member or a part of it is lost. In the wake of the Great East Japan Earthquake, a concept similar to structural redundancy was proposed for breakwaters to protect against tsunamis.[54] Developing new rational structures and design methods is a task to be tackled in the future. It calls for new steel materials with superior deformability and fracture resistance to conventional ones. Concerning the stratification of structures, on the other hand, as proposed in the national project "New Structural Systems,"[55] it is expected that "functional distribution" to distribute horizontal and vertical forces among different members of a structure will progress, and that the use of the most appropriate steel material for each place will be promoted. Regardless of which direction —redundancy or stratification—technology takes in the future, the performance required of steel materials, such as strength, deformability and fire resistance, will become more diverse and structures and their members that support safety will be expected to perform better.

5.2 Globalization and value of Japanese safety/security technologies

In view of the brisk activity in infrastructural development in the newly industrialized economies (NIEs), the demand for steel materials will be sure to expand rapidly in the future. **Fig. 16** lists the countries in order of consumption of structural steels, based on data made available by the World Steel Association (WSA) and the Japan Iron and Steel Federation (JISF) (some countries have been excluded due to a lack of official data). China is preeminent in steel consumption. India has already surpassed Japan and the United States. Mexico, Thailand, Brazil, Egypt, and Turkey, etc. are catching up with

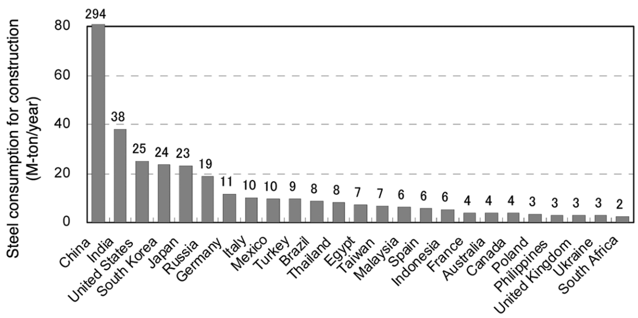


Fig. 16 Steel consumption in construction market by country (2010, WSA and other sources)

Germany, Italy and other industrialized countries. In terms of the per-capita consumption of structural steel and nominal GDP, India and Indonesia, etc. are far lower than the industrialized nations. Bearing that in mind, the growth potential for infrastructure in the world is great.

China and some other NIEs have developed their own design standards. Many of the NIEs, however, employ advanced design/construction techniques from the United States, Europe or some other industrialized country. The susceptibility to natural disasters, such as earthquakes, differs from country to country. Therefore, in designing and constructing a steel structure in a locality, it is necessary to give due consideration to the specific conditions of that locality. In particular, concern about earthquakes and tsunamis is growing around the world. In addition, with the improvement in living standards, the interest in protection of the environment of densely populated cities is mounting. Japan has the most advanced technologies for coping with earthquakes and landslides coupled with environment-friendly construction technologies. All in all, there is a good possibility that Japanese safety/security technology and environment-friendly technologies based mainly on steels will be able to play an important role in the global market.

5.3 Growing attention to sustainability

While the sustainable growth of society is discussed in earnest, the sustainability of infrastructure is rapidly attracting increasing attention. In the United States, Europe and Japan, environmental performance evaluation systems for buildings have already been proposed and put into practice (CASBEE in Japan)[56]. Those evaluation systems quantitatively evaluate the environmental performances of buildings in terms of environmental friendliness, running costs, and comfort for users, etc. In the future, infrastructural specifications, mainly for buildings, will be strongly influenced by those evaluation systems.

Steel materials are comparatively light in weight and have good seismic resistance, durability, recyclability, and can be easily dismantled, etc. Thus, they can be evaluated as highly sustainable materials. However, none of the existing environmental performance evaluation systems fully take those properties into consideration. **Table 1** compares the evaluation systems of Japan, the United States and Europe in terms of how much consideration is given to the advantageous characteristics of steel materials. It can be seen that they differ noticeably. In view of the expected growth of infrastructure on a global basis, the demand for its sustainability will increase and opportunities to fully utilize the properties of steel materials are expected to expand.

Table 1 Comparison of environmental design rating systems

Steel advantages	Japan (CASBEE)	United States (LEED)	Europe (BREEAM, EPD)
Strength	Considered	No	No
Ductile	Considered	No	No
Durable	Considered	No	Considered
Noncombustible	No	No	No
Recyclable	No	Considered	Considered
Dismantling	Considered	No	No
CO_2 emission	Considered	No	Considered

6. Conclusion

We have so far reviewed past changes in market conditions and market needs and the company's responses to those changes. We have also discussed the outlook for future technologies. In the first half of the text, we described how the change in the infrastructural environment has been brought about not only by the growth of society, but also by the changes in performance required of infrastructure as a result of disasters and accidents, and the development of innovative new technologies in steels. In addition, we have introduced the company's five characteristic activities (building large-scale infrastructure; improving seismic resistance; responding to urbanization; preventing deterioration/prolonging the life of infrastructure; and creating new trends). In the second half, as an outlook for future technologies, we discussed the possibilities of steel materials from these three standpoints: steel's role in ensuring safety; growth potential of steel in the world market; and response to the demand for sustainable infrastructure. In this technical review, we have seen that steels and their application technologies have progressed hand in hand with the development of infrastructure and have met the diversified needs of our ever-growing society, and that our company has been among the world leaders in technological development while creating new trends in steel technology. There is no doubt that steels will continue to be an important element in the support of infrastructure. Nippon Steel intends to continue developing advanced new technologies adapted to ever more diverse market needs and supply them to the world market on a timely basis.

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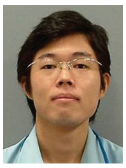

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