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Technological Development of Steel Structures through Construction of Steel-making Plants

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Abstract

After about 150 years since the construction of Japan's first iron bridge, Japan has become one of the advanced countries on steel structures. What made this possible was due partly to challenging developments by engineers in steel making companies through applications to various their own civil engineering plants. In this paper, the development history of steel structures technology through the construction of steel making plants was outlined with several examples, and then its future prospects were suggested.

1. Introduction

The development of Japanese steel structures technology started with the introduction of European and American technologies and the import of their iron and steel materials. The establishment of the Imperial Yawata Steel Works in 1901 that completed the preparations for full-scale production capability of the domestic steel material was a major opportunity to solidify the foundation for the autonomous development of steel structures technology in Japan. Since the 1960s, in line with Japan's rapid economic growth, the Japanese steel structures technology has made tremendous progress not only in structural design and system aspects, but also in steel material [1, 2]. All-out collective efforts of the industrial, academic and government sectors of the time have contributed as a strong driving force to the development of the technology. In the development, however, the bold challenges undertaken by engineers in steel making companies who took advantage of the construction of steelworks facilities and the field thereof should also be acknowledged.

Steelworks are sites wherein various facilities are integrated, and they can be deemed not only as a base for the efficient production of steel material, but also as a miniaturized version of the infrastructure that sustains our society. Plant engineers in steel-making companies have continually made efforts to shorten the construction period and to reduce the construction cost of the buildings and foundations in the steelworks, which are very crucial in the construction schedule of an entire plant facility project. Through these efforts, they have taken on the challenge of technological development on their own by incorporating the state-of-the-art technologies of the time. At the same time, they have also developed appropriate application technologies for providing the construction market with their own steel products by using their construction fields.

The outcomes of the various activities undertaken in steelworks have been widely utilized as the technologies to strengthen the infrastructure in Japan and moreover, they have become a driving force behind the development of the Japanese steel structures technology, which is a global frontrunner today. In such activities, two technological development patterns for utilizing the plant construction fields have evolved simultaneously in parallel. One is the development mainly to verify and demonstrate technological seeds obtained in research; the other is needs-oriented development to directly solve the needs and/or problems encountered in the construction of steelworks facilities. These characterize the technological development activities in steel-making companies. In this paper, the history of the steel structures technology developed by utilizing the steelworks fields is outlined with several examples, and then, its future prospects are described.

2. Social Needs and Steel Structures

Historically, the country has been rocked by various disasters and accidents including major earthquakes. Undoubtedly therefore, one of the factors that realized the economic growth of disaster-prone Japan is the robust infrastructure such as bridges, buildings and so forth. Since the 1960s, several comprehensive national land development plans have been proposed and executed as important state policies. Through a series of such development plans, laws and design standards have also been revised to provide infrastructure with larger structural robustness. Quickly responding to and supporting the changing trends are, in fact, the steel structures and the steel materials.

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Table 1 Timeline of various events, changes of codes and standards, and major steel materials and products

	Before 1960	1960s	1970s	1980s	1990s	2000s	2010s
Events such as national plans and disasters	▼'59 Ise-bay Typhoon	▼National Development Plan; Niigata Quake ▼; ▼Tokachi-oki Quake; ▼New Dev. Plan (Exp. way & railroad)	▼The 3rd Dev. Plan (Energy); ▼Miyagiken-oki Quake	▼The 4th Dev. Plan (Multipolar land formation)	Great Hanshin Quake▼; ▼Hokkaido Nanseioki Quake; ▼The 5th Dev. Plan (Self-reliance community)		Great East Japan Quake▼; Hiroshima Landslide▼
Laws, codes and guidelines		Noise Regulation Act▼	▼Vibration Regulation Act	▼Revised Building Standards Law (New seismic design)	▼Revised Bridge Specifications (New seismic design)		Passive Control Design Guidelines for Buildings ▼
Major steel products for construction	▼'31 Steel sheet pile; ▼'55 Light-gauge hot-rolled shape; ▼'59 Hot-rolled H-shaped beam	▼Steel pipe pile; ▼Weathering steel (COR-TEN)	▼Roll-formed box column	Drilling & pressing pile driving (TN)▼; Fire resistant steel ▼; Low yield strength (LY) steel, New hot-rolled beam (Hyper beam), Low YR 600MP class steel ▼; ▼Buckling restrained brace (Unbonded brace system)	Soil cement mixed pile driving (Gantetsu) ▼; SN steel (Seismic resistant) ▼; ▼Bolted frame system (Hyper frame system); ▼Super high-tension bolt (SHTB)	▼Screw pile (NS ecopile); High strength drilling & pressing pile driving (TN-X)▼; ▼Hat-shaped steel sheet pile; High performance steel for bridge (SBHS)▼; 1000MPa class steel (HT880) ▼	

Table 1 shows the chronological arrangement of the following items since the 1960s [3]; the major social movements and events, revisions in codes and standards related to construction, major construction materials and technologies developed. The timetable in Table 1 reveals that various steel-structure-related products and technologies have been developed in accordance with the change in society. As typical examples of the development, the following two cases can be given. The first case is that with the enactment of the Noise Regulation Act in the 1960s and the Vibration Regulation Act in the 1970s, noise and vibration had to be reduced especially in steel pipe piling methods, and thus various piling methods emerged in the market. The second case is that the Revised Building Standards Law enacted in the 1980s to cope with frequent large earthquake disasters encouraged the creation of various steel materials, structural members and devices for increasing the seismic resistance of the buildings.

The revision of such regulations and design methods was applied not only to the construction market, but also to the steel-making facilities without exception. Accordingly, within steel-making companies, extensive efforts for promoting technological improvement and development have been made in both plant construction and product development. Consequently, steelworks functioned not only to simply produce and provide steel materials, but also to provide testing sites for the development of the application technologies, thus encouraging the application of steel materials in the market. A tight relationship existed between the plant engineering technology in steelworks and the steel structures technology for the infrastructure in Japan.

3. Early development of Steel Structures (in the 1910s)

The first infrastructure to use steel and iron based materials in Japan was the Kurogane Bridge (constructed of wrought iron) that dates back 150 years. Development of Japanese steel structures technology was delayed behind the advanced countries in the world by about one hundred years. Following the Kurogane Bridge, several steel and iron based bridges and buildings were built. However, in reality, they mostly relied on the materials and the design technologies that were imported from Europe and the USA.

The autonomous growth of steel structures in Japan started after the establishment of the Imperial Yawata Steel Works and development of the steel structures was considered to be triggered by the construction of a factory building (Roll-turning lathe factory, **Fig. 1**)

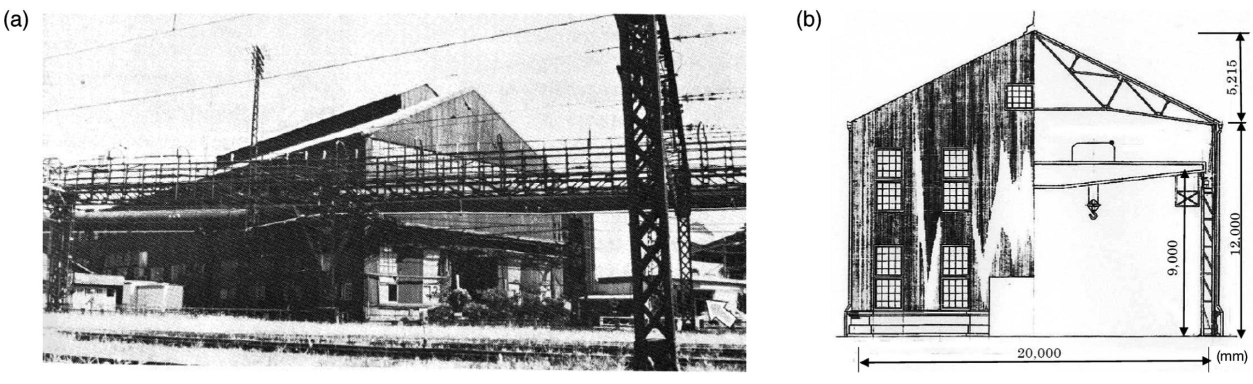


Fig. 1 Roll turning lathe factory in the Imperial Yawata Steel Works [4]
(a) Roll turning lathe factory (a photo taken in 1976), (b) Side view

in 1909 designed by Mr. Kageyama, a young engineer of the Yawata Steel Works at that time (later he became the director-general of the Yawata Works of Japan Iron & Steel Co., Ltd.[4]). According to Hirakida[4], the roll-turning lathe factory is one of the earliest large-scale steel structures that were built with domestically produced steel material and designed solely by Japanese engineers.

After that, the steel structural system was applied to factory buildings of steelworks and various buildings of military facilities. It has continued up to the present day, solidifying its foundation of the development of steel structures. As Hirakida states[4], Japanese plant engineers constructed large-scale steel structure factory buildings by using the technologies of Europe and the USA as a reference while imploring the Japanese universities that held the state-of-the-art technologies of the time. As suggested through this fact, the advancement of the steel structures was strongly supported by the aggressive spirit of the plant engineers that took on the challenge of constructing steel-making facilities in spite of the serious risk involved. From the outset, the development of steel structures owed much to their utilization of the steelworks construction field as the motive power.

4. Development of Application Technologies of H-section Steel (in the 1960s)

The development of the large scale steel material production and the steel structures technology started after the 1960s when Japan enjoyed an era of rapid economic growth. During the period, various steel materials such as H-section steel shapes, light-gauge steel section shapes, high-strength deformed bars, etc. were developed, produced and supported the robust construction demand at that time. Among them, rolled H-section steel shapes greatly contributed to the development of steel structures. The production and the sales of the H-section steel shapes started in 1959 and with the development of design and connection technologies, the shapes are now used widely, especially in building frames.

The 1960s were also a period of rapid economic growth and the requirements for the improvement of the productivity of building construction grew sharply. To address such a situation, Yawata Iron & Steel Co., Ltd. of the time proposed and developed the new "MONO-H Construction Method," employing H-section steel shapes as the primary members[5]. This construction method was a structural system having the following features (**Fig. 2** (a)): application of H-section steel shapes to both the columns and the beams, optimized arrangement of the weak and strong axis directions of the H-section steel columns to withstand the seismic forces, and finally application of high tension bolts to the connections of the members.

The idea of the MONO-H Construction Method was proposed in the 1950s and subsequently the method was applied extensively to the company houses of steelworks and the company's R & D buildings (Fig. 2 (b))[6]. Although the extent of the contribution of the plant engineers to the development and application is not completely transparent, it is one of the examples of the energetic development of the application technologies for steel construction materials by utilizing the construction fields of steelworks and the related facilities.

Although the MONO-H Construction Method did not become wide spread in the market due to the advent of welding technology and box-type columns, the method had favorable effects on the subsequent development of steel structures either directly or indirectly, mainly in the field of the prefabricated steel structural systems that emerged later. Although the method was proposed about 50 years ago, the technology had the foresight to ensure that it would be able to comply with even current needs directly.

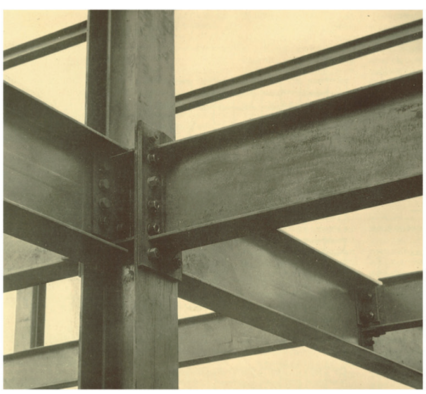
5. Development of Concrete-filled Steel Tube Structure, New Composite Structure (in the 1980s)

The concrete-filled steel tube structure (CFT) is generally used in high-rise buildings and in ultra-high rise buildings nowadays. Historically, the technology was applied at its relatively early stage to equipment supporting steel frames in steelworks in the 1980s. Further to the design technology, the mix proportion of the filling concrete and the concrete placement (pouring) technique were studied. Although the CFT structure is a rational system wherein steel and concrete are reasonably combined (**Fig. 3** (a)), considerable time was required for the practical application because the structure was not approved by and was out of the scope of the Building Standards Law in Japan at the time.

In the 1980s, through the strong demand for energy saving, many coke dry quench equipment (CDQ) facilities were built. This type of equipment was built in a top-heavy loading condition wherein special consideration in the seismic design was required. As higher rigidity, higher strength and higher deformation capability were required for the supporting structure, the CFT structure, still at the research stage at the time, was considered most suitable for that purpose (Fig. 3 (b)). Thus, the research and development of the CFT structure by plant engineers were conducted extensively at an earlier time[7].

In addition to the research on the structural performance of the CFT column and the beam-column connection, the research on the

(a)



(b)

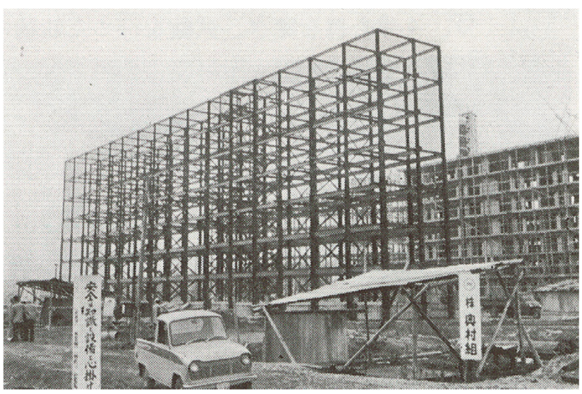


Fig. 2 MONO-H structural system and its application to family housing for steel making company[5, 6]
(a) Detail of MONO-H structural system, (b) No. 9 Hanada family housing for steel making company

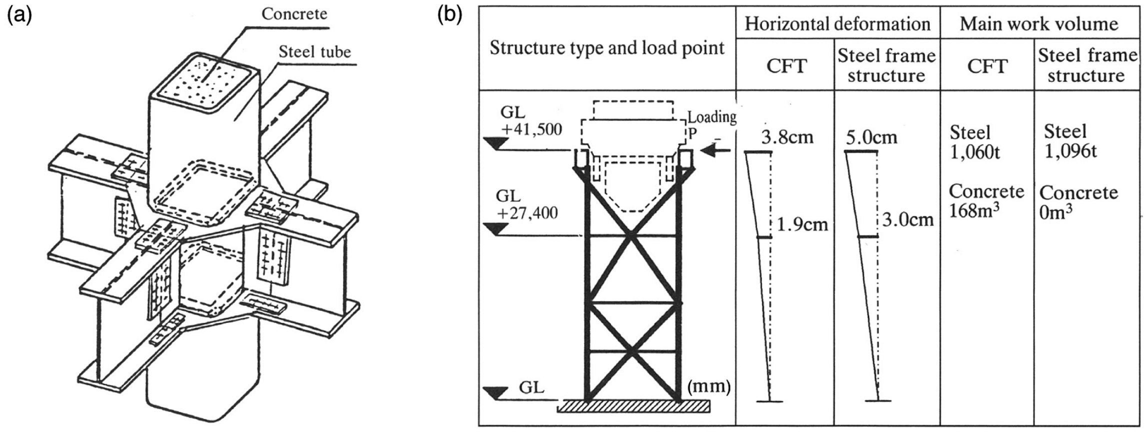


Fig. 3 CFT structure and its features [7]
(a) Outline of CFT structure, (b) Comparison with steel frames for a CDQ equipment

pump-up concrete placement method, which is an efficient method that fills in concrete by pumping from the lower section of the column, and the research on the mix proportion of the filling concrete were conducted. Then, the results of the research were applied to the supporting frames of the six CDQs built during the period between 1985 and 1989 [7]. These research activities became the basis of the later wide prevalence of the CFT structure in the building market, eventually leading current popular applications in high rise buildings in Japan.

6. Development of New Foundation Method, Continuous Steel Underground Wall (in the 1980s)

In the 1980s, the need for highly reliable underground walls rapidly rose along with the growth in scale of the steel-making facilities and buildings, as well as with the increasing needs for the effective utilization of underground space. Although reinforced-concrete-based continuous underground wall (diaphragm wall or slurry wall) methods existed at that time, most of such walls remained for use as temporary retaining walls because of its large variation in quality, which was caused mainly by on-site concrete casting work. Therefore, the development of the steel underground wall was initiated, with the target of enhancing quality, reducing wall thickness and shortening the construction period by using prefabricated steel elements for the wall, so that the new wall system would encourage and expand the permanent use of the underground wall (**Fig. 4** (a)) [8].

The steel elements and construction methods were developed so as to comply with various projects and site conditions while maintaining high quality. Using the steel elements, new composite structural walls with steel and concrete and the corresponding construction methods for such walls in the ground were developed. Some of the developed construction methods include: one shown in Fig. 4 (b) [8, 9] of installing large-scale steel elements in the ground in a trench excavated while preventing the collapse of the trench by using a stabilizing fluid, and the other of pressing relatively small-scale steel panels into the ground while drilling from the inside of the panels. In the steelworks where permanent walls were strongly preferred for economic and time constraint viewpoints, the developed construction methods were considered to be suitable and applied to several plant projects, enjoying various benefits such as lowered cost, shortened construction period and so forth.

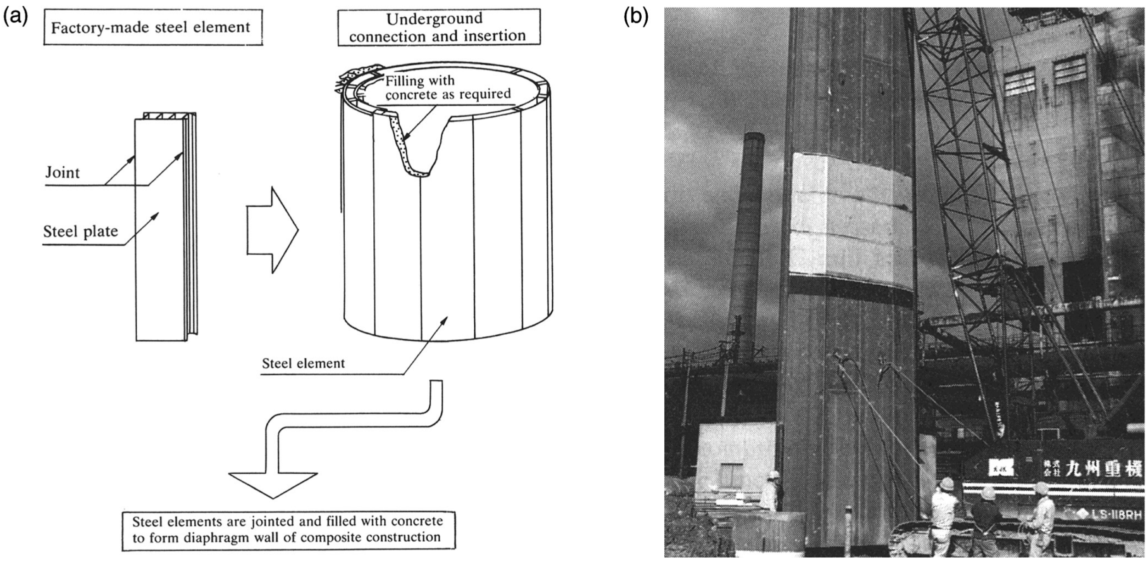


Fig. 4 Outline of continuous steel underground wall and its application example [8]
(a) Outline of continuous steel underground wall, (b) Installation of large scale steel panel

Later on, the structural systems and construction methods were applied as continuous steel wall systems to the construction market mainly for facilities such as a subway construction site wherein the wall thickness and the space availability were limited [10]. Separately from the steel continuous wall, steel sheet piling methods have been used for earth retaining for many years and the sectional size of steel sheet pile has become enlarged. This enlargement might be considered partly influenced by the continuous steel wall proposed and developed previously. As the above examples show, the continuous steel wall developed through the construction projects of the steelworks contributed to increasing the reliability of the underground wall and encouraging the size enlargement of the steel sheet pile.

7. Development of Building and Foundation Systems meeting Labor-saving Requirements (in the 1990s and Later)

In line with the rapid economic growth in the 1990s, short construction period and labor-saving were strongly required in the construction field. It was also the period during which there was active investment in energy-saving equipment in steelworks. Because of the investment purpose, the equipment was required to be started up as early as possible to gain its full benefit. To correspond to the needs of both the construction market and the in-house equipment investment, the development of time-saving and labor-saving technologies for buildings and foundation structures was started. The representative technologies are the bolt-connection frame system and the one-pile/one-column foundation system.

Traditionally, the columns and beams of steel buildings have been connected with welds. In this type of building frame, securing of highly skillful welding operators and the engineers for inspection to control the quality of welding was problematic. To solve these problems, the all-bolted frame system was considered [11], where all the connection work at the construction site is done by using high tension bolts. This frame system can shorten the construction period drastically, simplifying quality control and eliminating the need for employing highly skilled workers and qualified engineers. For box columns having a closed section used typically in Japan, the bolt-connection becomes difficult in the conventional manner; therefore, a new high tension one-side bolt was also developed. The developed system was applied to the buildings in steelworks at first (**Fig. 5**), and then its wider spread into the building market was targeted.

Although government permission for the technology was obtained, the need for labor-saving was weakened by the influence of the economic slump in the 1990s, and as a result, the all-bolted frame system was not accepted widely in the market. However, this system encouraged the development of novel high tension bolts such as super-high-tension-strength bolts (SHTB) with a ultimate strength of 1400 N/mm^2. Recently, needs such as labor-saving, multi-skilled workers and shortening of the construction period have increased rapidly again. As a result, the all-bolted frame system will be reevaluated and gain popularity again in the future.

On the other hand, regarding the foundation structures, the conventional type of foundation is one where the columns are supported by a reinforced concrete foundation that is further supported by a number of piles. However, the construction of the reinforced concrete foundation and the related underground beams that connect the foundations were an inhibiting factor in shortening the construction period. To solve this problem, in the late 1980s, a new foundation system was proposed and developed wherein one-column is connected with concrete to a large-diameter steel pipe pile by directly inserting the column into the pile (**Fig. 6**) [12]. A technological challenge was undertaken in the detailing and design methodology of rigid column-pile connection [13]. Similar to the all-bolted frame system, the system was applied to the construction projects in steelworks (applied to more than 400 piles), enjoying the advantages of the shortened construction period and labor-saving. At the same time, the acquisition of government permission was realized, aiming at wider applications in the construction market in Japan. The one-pile/one-column system is called “sat-in-pile,” and was also adopted in a famous natural gas resource project in Australia where the needs for labor saving were extremely strong. This can be regarded as a symbolic case in which a technology developed in steelworks has been applied and spread in the global market.

8. Development of Health Evaluation Technology for Corroded Steel Structures (in the 2000s and Later)

In line with the progress of social maturation, the deterioration of infrastructure such as bridges has become a serious problem, and therefore, the development of its health evaluation technology becomes of paramount importance. Steelworks in Japan, which are located in a coastal area and have been operated for a long time are no exception to the deterioration. In steelworks, the problem is especially serious in belt conveyer support frames that are typical out-

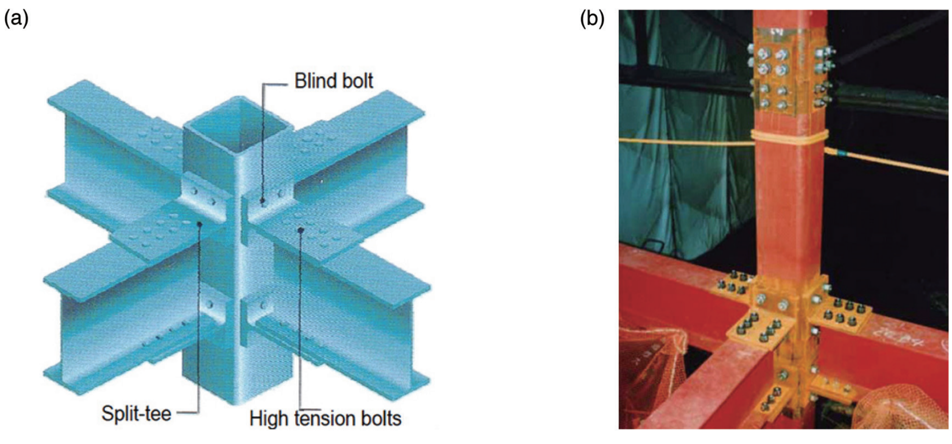


Fig. 5 Outline and application example of all-bolted frame system
(a) Outline of all-bolted frame system, (b) Application example to a steelworks facility [11]

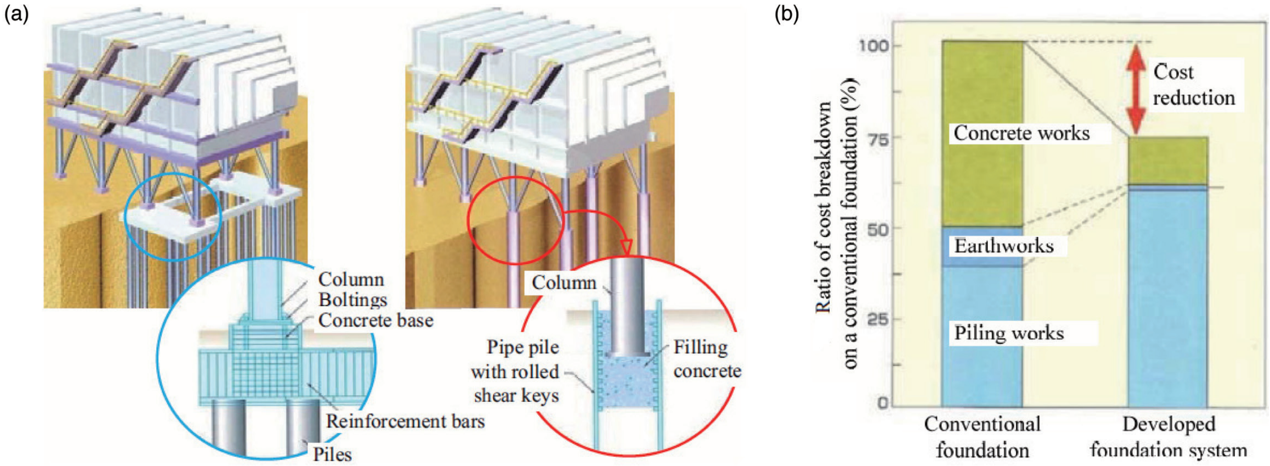


Fig. 6 Comparison between developed one-pile/one-column foundation and conventional foundation systems [12]
(a) Comparison of structural detail, (b) Comparison of cost

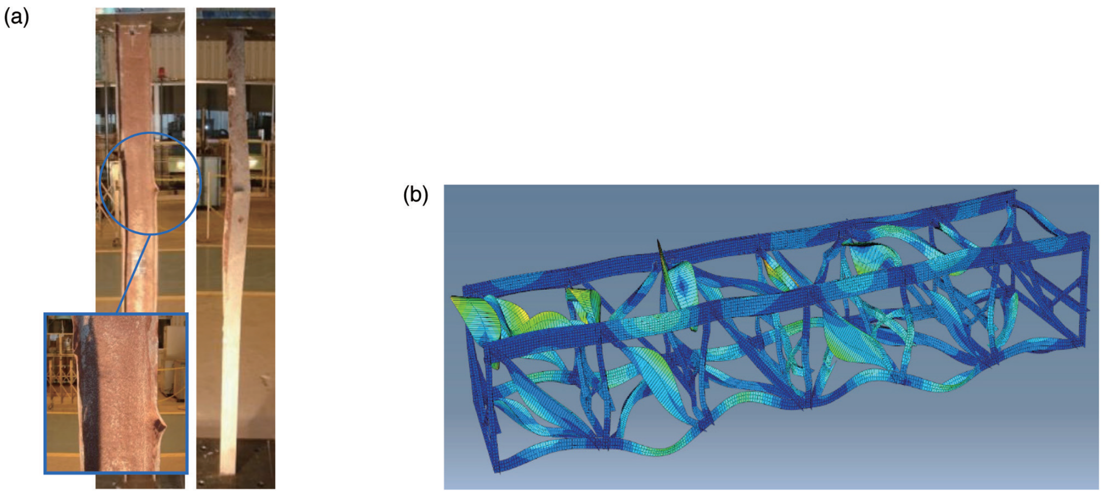


Fig. 7 Strength evaluation of corroded member and damage evaluation of truss system
(a) Column buckling test of corroded member [14], (b) Damage evaluation based on high frequency vibration mode

door structures exposed to a severe corrosion environment.

Under such circumstances, extensive studies have been conducted on the residual strength of the belt conveyor supporting frames by considering the degree of corrosion of each member in the frames, and by extracting the higher vibration modes of the frames and their members (**Fig. 7**) [14, 15]. Through these research activities, the following valuable knowledge has been obtained: the residual strength of a member can be evaluated based on the section properties defined at the minimum cross section of the member [14]; the extent of the corrosion degree may be estimated by the information on the higher vibration modes of the targeted member [15]. In these research activities, various belt conveyor support frames used in steelworks have been directly utilized to verify the research findings. For example, the sample members for compression tests were taken from the corroded support frames in steelworks and the higher vibration modes were investigated directly using the supporting frames in operation in steelworks.

These activities are currently ongoing, but the technologies are expected to provide reasonable damage evaluation and life estimation for proper maintenance control, which will become exceedingly important as the social maturity progresses. Furthermore, as infrastructure such as bridges and industrial infrastructure including steelworks have much in common, the steelworks can continuously provide a valuable research opportunity for realizing a sustainable society.

9. Conclusions and Future Prospects

As one of the driving forces that developed the steel structures technology in Japan, several examples of the technological development that utilized the steelworks field were discussed. Applications in the field are indispensable for the development of the steel structures, their materials and construction technologies that support the infrastructure. An overview of the history of the development of past steel structures technology reveals there was a strong contribution from the plant engineers who continually took on the challenge of these new technologies with inherent risks in the construction of steelworks. Such a challenging mindset is akin to the DNA inherited from the initial establishment of the Imperial Yawata Steel Works. Although the wide acceptance of some of the developed technologies in the market often failed due to changes in the circumstances and so forth, there are many technologies that would satisfy the current needs of the market when their features are reevaluated.

The steelworks field is regarded as a miniaturized version of the infrastructure, and the subjects encountered in the construction of the steelworks are the same as those seen in the market, and vice versa. Subjects that surround the infrastructure are becoming more complicated than ever as the phase of the subjects changes from the new construction stage to the maintenance control stage, or from the initial cost stage to the life-cycle-cost stage. It is important to propose and develop new technologies that can respond to the changes in the circumstances in a flexible manner, apply the technologies to the plant construction of steelworks so that the steelworks can enjoy the merits, and continue to furnish society with new technologies in a timely manner. Developing the state-of-the-art technologies for steel structures while inheriting the history and the tradition shown in this article is an important mission for the civil engineers in the steelworks, and it is important to contribute to the growth of the sustainable society through such activities in the future.

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