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DX Challenges in Azabudai Hills

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Introduction

Issues surrounding the construction industry have been changing at an accelerated pace, including a shortage of construction workforce, an increase in unskilled workers, and changes in work styles in the recent past. In addition, projects are becoming more complicated, requiring adherence to construction delivery period and high quality.

Under these circumstances, in order to stay ahead of the competition, there is a need to transform work styles and improve productivity.

Azabudai Hills is located in the area connecting Kamiyacho on the Hibiya Line and Roppongi 1-chome on the Nanboku Line operating in Tokyo, and was planned as a district with three skyscrapers arranged around a plaza. Based on the concept of a "Modern Urban Village," the project integrates a variety of urban functions, including offices, residences, a hotel, an international school, commercial and cultural facilities. The construction of the 64-story and 330-meter-high "Mori JP Tower" was extremely difficult due to its large scale and diverse uses.

This article presents a case study of "DX" initiative—IT tools and digital technologies applied at the Azabudai Hills—to improve productivity and ensure quality, as well as the resulting benefits and future challenges.

Building Outline

- Location: 1-Chome, Azabudai, Minato-ku, Tokyo
- Building type: Offices, residences, retail, medical facilities, international school, cultural facilities, e.g.
- Developer: Toranomon-Azabudai District Urban Redevelopment Association
- Designer: Mori Building Co. Ltd., Nihon Sekkei, Inc., Shimizu Corporation
- Main contractor: Shimizu Corporation
- Building area: 5,300 m^2
- Floor area: 461,800 m^2
- Floors: 5 basement floors, 64 floors above ground, 2 floors of penthouse
- Building height: 330 m
- Steel frame weight: 130,000 tons

Structural System of the Main Tower

• Frame System

The structural plan of the main tower is shown in Fig. 1. The main tower is a steel-framed, rigid moment-frame structure with braces. The building is designed based on a seismic response control method that absorbs seismic and wind energy using damping devices installed in the building. The columns up to 52nd floor are concrete-filled tubes (CFT) to enhance their bending rigidity and bearing capacity. Horizontal stiffness and bearing capacity of the building

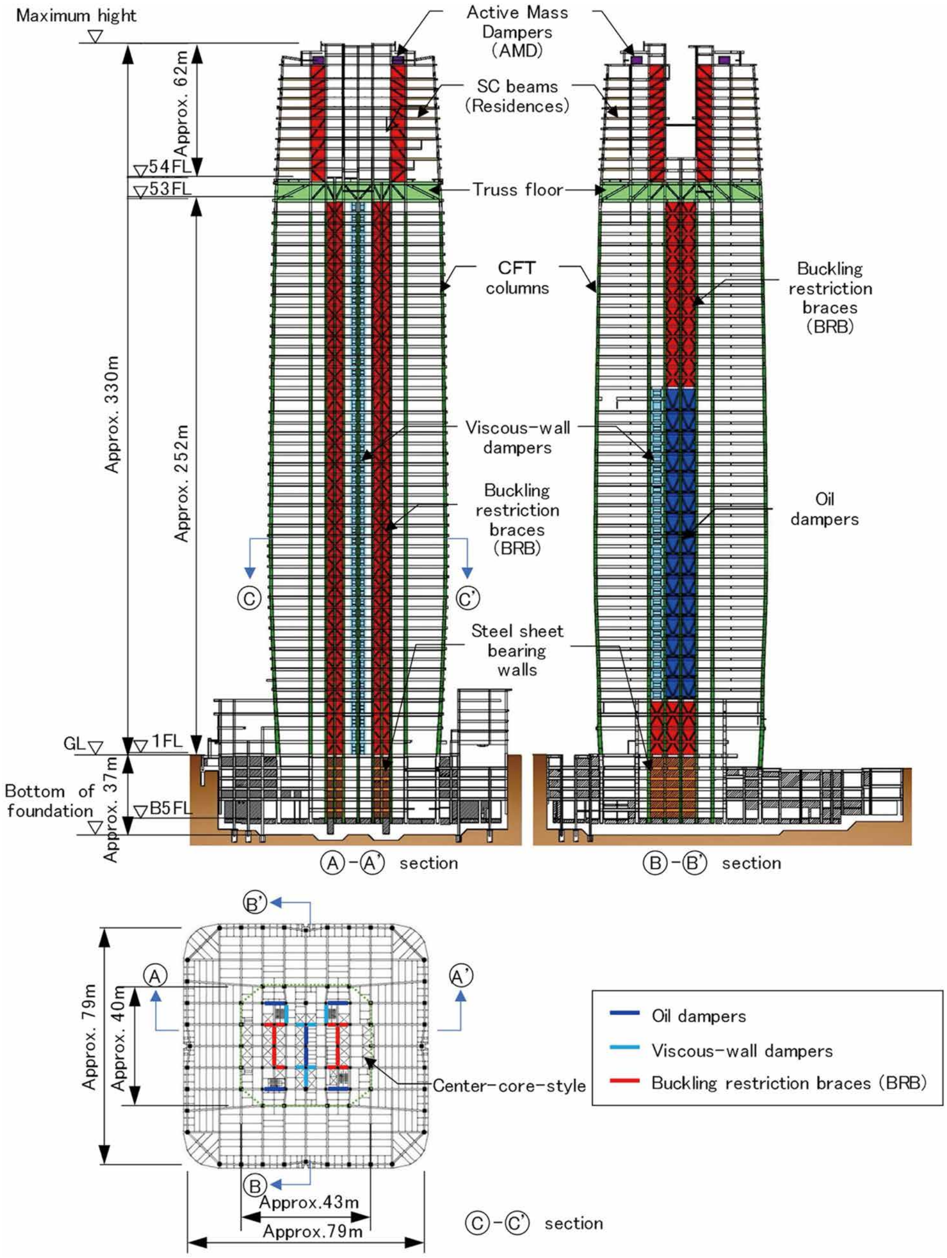
Photo 1 Perspective of Azabudai Hills

are improved with buckling restrained braces (BRB) installed in the core area.

Because of the different column spans for the residential and office floors, the 53rd floor is designated as a structural transfer floor, where full-floor truss frames are incorporated to relocate the columns. For the residential floors above 54th floor, steel-concrete composite beams (SC beams) are adopted to reduce heavy floor impact noise. The BRBs are primarily placed in the core to stiffen the frame. On the roof of 64th-floor residential section, active mass dampers (AMD) are installed to enhance habitability against wind and mitigate post-earthquake vibrations rapidly.

Column sizes are up to 1,400 mm for square sections and 1,600 mm for circular sections. The typical beam height is 1,200 mm and their long span length is 17.8 m. The core frame plan features a center-core style measuring approximately 43 m by 40 m in plan. The building's outline is characterized by gently curved lines, and consequently, the floor plan of each level subtly adapts to this curvature. At the lowest level of the curvature (1st basement floor), the plan measures approximately 72 m square and the surrounding beam span is about 14.4 m. In the middle layers, where the outline expands outward, it measures about 79.2 m square and the beam span expands to 18.0 m. At the top layer, it is approximately 70.5 m and the beam span is about 13.7 m. Each perimeter column is slightly bent at column-beam joints to conform to the building's outline.

Figure 1 Structure Frame of the Tower

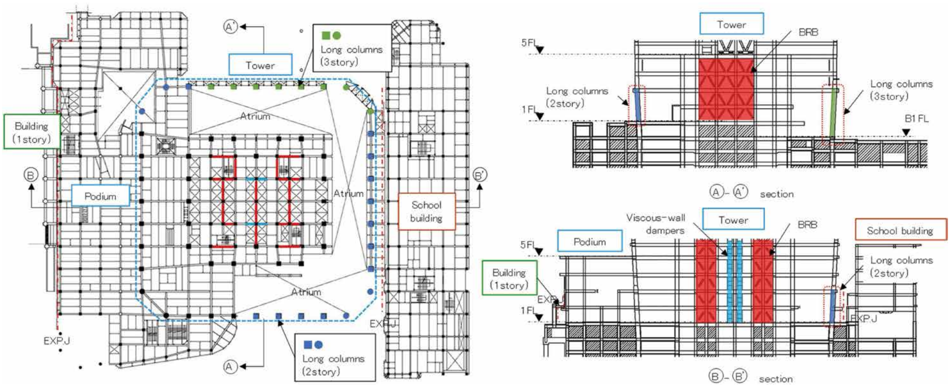


• Damping Device System

We adopted velocity-dependent oil dampers and viscous-wall dampers as damping devices, as they are effective across a wide range of amplitudes, from small vibrations caused by wind and moderate earthquakes to large-scale seismic events. These devices are installed in the core from 5th to 52nd floors, with a concentration between 5th and 34th floors where story drifts are relatively large to absorb energy efficiently. The oil dampers are strategically placed to span two stories skipping one floor, thereby doubling their effective velocity and enhancing energy absorption efficiency.

Entrance rooms and retail stores in 1st basement floor to 4th floor have high story height around 6.0 to 6.2 m. And due to a large atrium, as shown in Fig. 2, the perimeter columns are designed as 'long columns' which have more than 8

Figure 2 Structure Frame Plan of Podium



length/diameter ratio. Because more than half of the columns of the tower are long columns, braces are placed in the core to keep horizontal stiffness. On south, north, and west sides of the tower, there are one to four stories buildings. Those low-rise buildings and the tower are planned as a single structure. Although the podium has unbalanced placement which causes larger eccentricity ratio of the tower, it contributes to gain horizontal stiffness and torsional stiffness.

DX Strategy of Shimizu

The three pillars of our mid-term digital strategy, "Shimz Digital General Contractor," are "Digital Manufacturing," "Digital Support for Manufacturing," and "Provision of Digital Spaces and Services." Definition of a "Digital General Contractor" is the construction company that digitally carries out manufacturing and provides both real and digital spaces and services, based on the knowledge of real manufacturing and cutting-edge digital technology.

In this project, we adopted a next generation production system shown in Fig. 3 and named "Shimizu Smart Site" in which AI-equipped autonomous construction robots and humans collaborate to carry out construction work efficiently, to promote the digitalization of construction management, and to operate the site with an eye toward the next generation.

Initiatives in Azabudai Hills

• Smart Control Center (SCC)

The Smart Control Center, shown in Photo 2, is a centralized monitoring room for the site. 36 units of 55-inch OLED displays were installed to collect and display all kinds of information on the site.

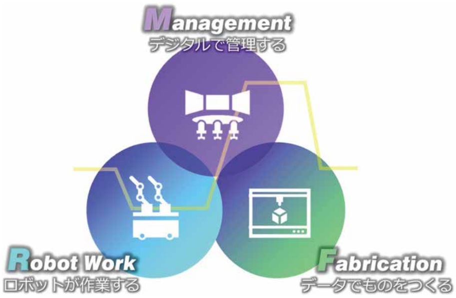
Images from surveillance cameras attached to tower cranes allow erection work 300 m above the ground to be viewed in this room. It significantly reduces travel time within the site.

In addition, workers were aware that they are constantly being watched, and this has improved their safety awareness.

The Smart Control Center also provided other real-time status information, such as deflection of the retaining wall, vibration and noise, and weather conditions, all of which were digitized and stored.

Until now, the construction industry has not captured data on the construction process, and its experience and expertise have been difficult to share. The challenge is to use AI to analyze these construction data in the future and utilize them to develop better plans for the next project.

Figure 3 Shimizu Smart Site



• Monitoring System

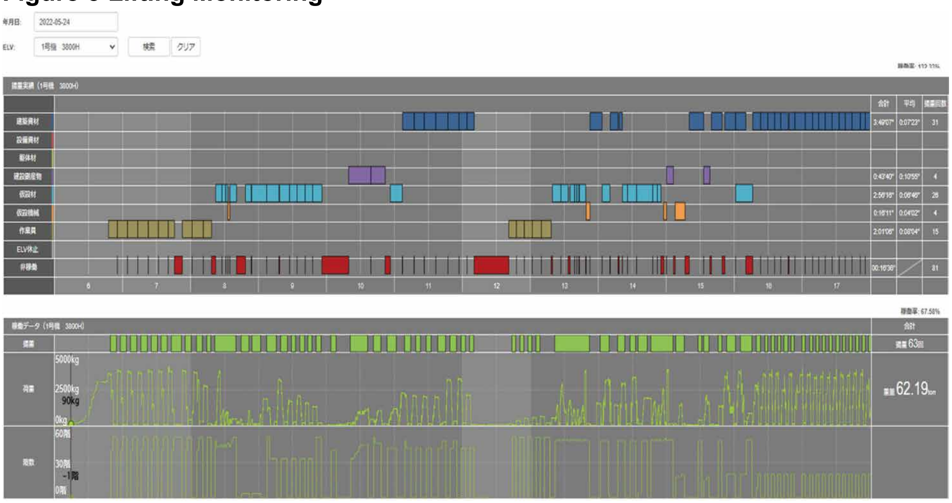
Fig. 4 shows an overview of the operational status of tower cranes and temporary lifts monitored by the Smart Control Center. Efficient lifting of people and materials is an important control point at a skyscraper construction site, and the operation status of six tower cranes and six temporary lifts is monitored.

Fig. 5 shows an overview of the data from a temporary lift. The above part of the figure shows the name of the material, the number of floors to be delivered, the name of the contractor, etc. which are registered by the temporary lift operator

Photo 2 Smart Control Center (SCC)

Figure 4 Monitoring System

Figure 5 Lifting Monitoring



using iPad. The lower part is the automatic display of the load and the floor number to be reached and obtained from temporary lift. In the future, we are considering using AI to automatically identify and record the number of workers and types of materials as well.

Fig. 6 shows the number of counts for the times of lifting at each floor by construction and job type. Six temporary lifts are monitored, and all the lifting data is stored in a cloud server, on which AI is used to automatically calculate the lifting frequency and analyze the lifting data. The data is then used to improve daily lifting management and as reference data for other projects, throughout the company.

Fig. 7 shows the analysis of the recorded elevator usage data with the addition of a time axis. The construction of the typical floor of a high-rise building proceeds to the upper floors, repeating the same procedure for each floor. Building materials of each construction type must be lifted in a timely manner in accordance with this cycle. By overlaying this data with the actual weight lifted to each floor and the process, it is possible to determine whether the construction progress is on schedule.

Figure 6 Lifting Results by Floor (number of lifts)

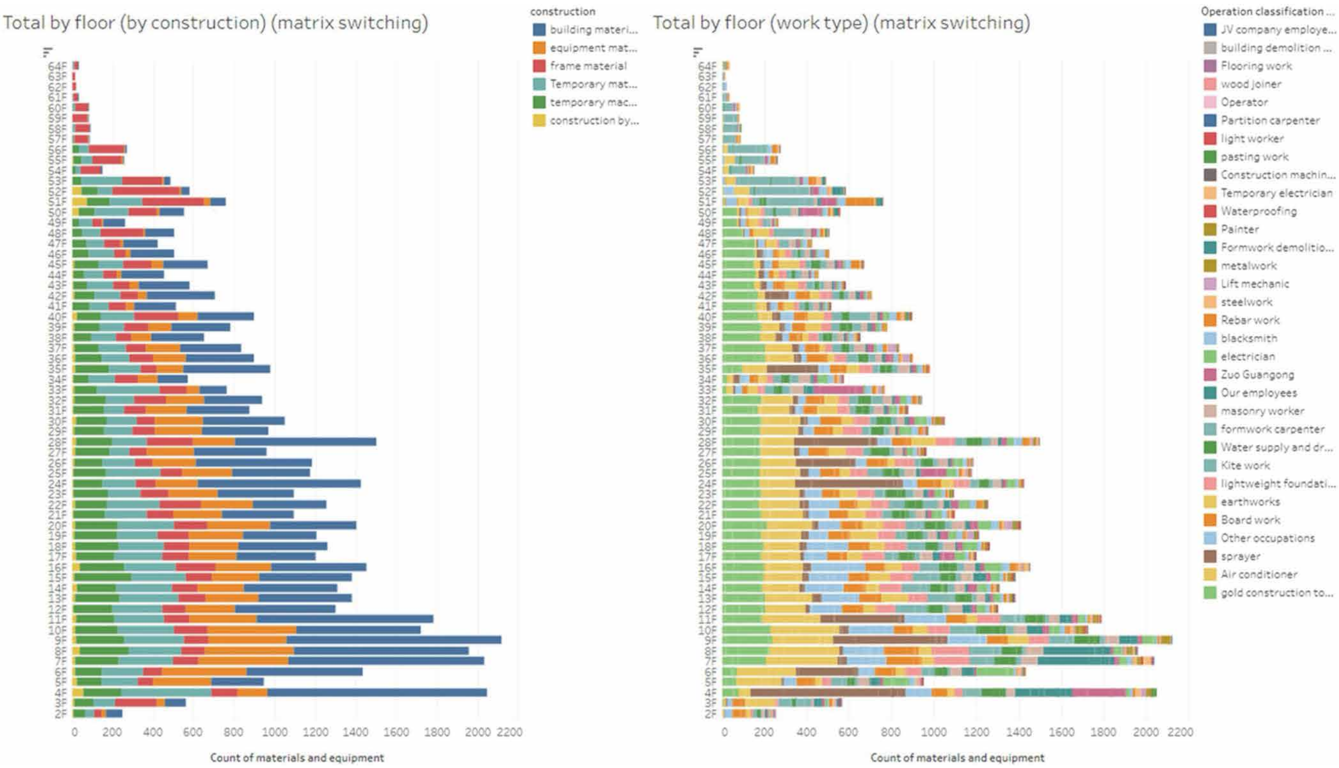
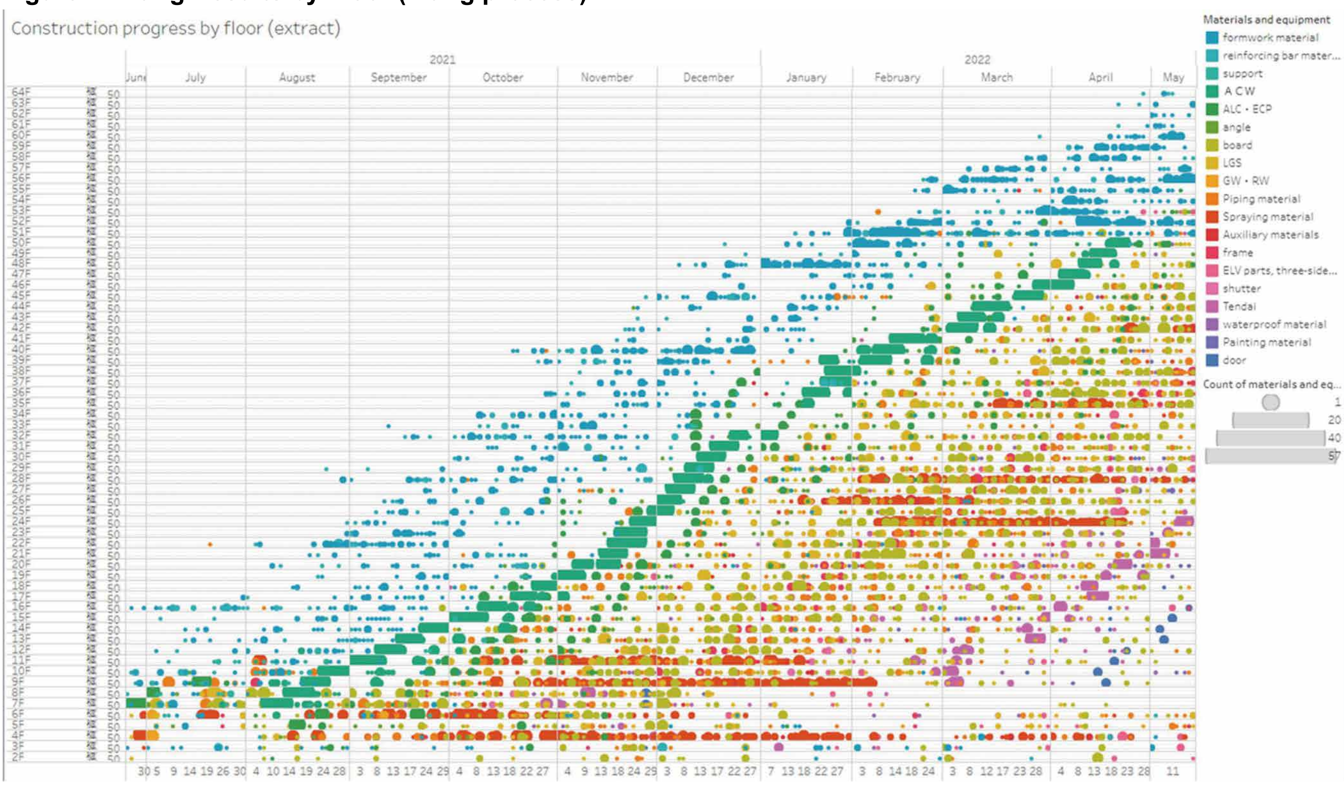


Figure 7 Lifting Results by Floor (lifting process)



• Smart Station

Fig. 8 shows the Smart Station developed as a next-generation distribution board. It is a distribution board with a 32-inch touch display and has the following three features.

1) IoT of distribution boards enables breaker monitoring and remote operation.
2) Serves as a platform for on-site communication infrastructure with Wi-Fi functionalities.
3) On-site communication tool

The IoT system for the distribution boards enabled remote operation in the system shown in Fig. 9. As such no longer necessary to patrol on site to turn off the lights. In addition, the 360-degree camera installed on the distribution board stores images, allowing the operator to check not only the current status but also the past status (Fig. 10). In the future, the company is considering using the system to check the progress.

Photo 3 shows the morning meeting at the job site. As a communication tool, the day's site layout and process chart can be displayed and viewed with a single click on a touch monitor. In this project, due to a Covid-19 measure, morning meetings were held at each work area. Workers gather at the Smart Station in each area, confirm the instructions for the entire site, and then hold a morning meeting for each area.

In this way, the Smart Station brought about improved productivity among workers.

• Utilization of Construction Robots —Robo-Carrier

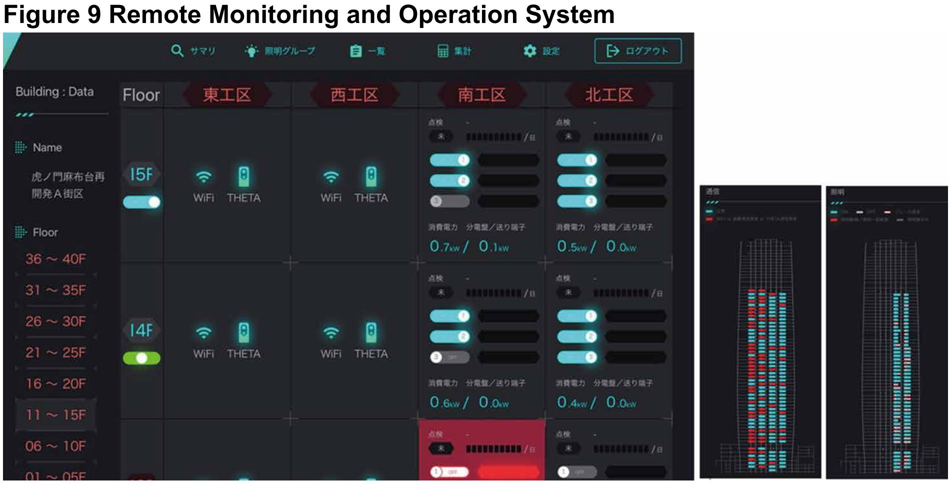
The transfer robot shown in Photo 4 was used to efficiently transfer the large number of materials brought in daily to the construction floor. Automated transfer systems are generally operated by linking an automatical-

Photo 3 Morning meeting with Smart Station

Photo 4 Robo-Carrier

Figure 8 Smart Station

Figure 9 Remote Monitoring and Operation System



ly operated temporary lift with a robot for loading and unloading. In this case, the waiting time for the temporary lift would be long, so in this project, the loading was done by workers, two robots were used for loading and unloading on the construction floor, and horizontal transportation of temporarily placed materials was done during break time, prioritizing the operating efficiency of the temporary lift.

—Robo-Welder

Photo 5 shows the welding robot and Photo 6 shows the welding procedure by the robot. Welding is one of the most difficult tasks at construction sites. The welding robot, which performs this task in place of workers, can detect each weld line, recognize its shape, calculate the target position of the next weld line, and weld. By recognizing the shape of the weld line, even thick plates of 40 mm or more can be welded without defects. In addition, the system was designed to accommodate root gaps from 5 mm to 11 mm, reflecting actual field conditions. Various tests were conducted on site, and after passing the tests, the columns were welded.

—Robo-Spray

Photo 7 shows a fireproof coating spraying robot. The robot arm performs the spraying and is programmed to handle the duct holes and ribs of large beams. It can spray to the soffit of the beam's bottom flange without material falling, just like a professional human.

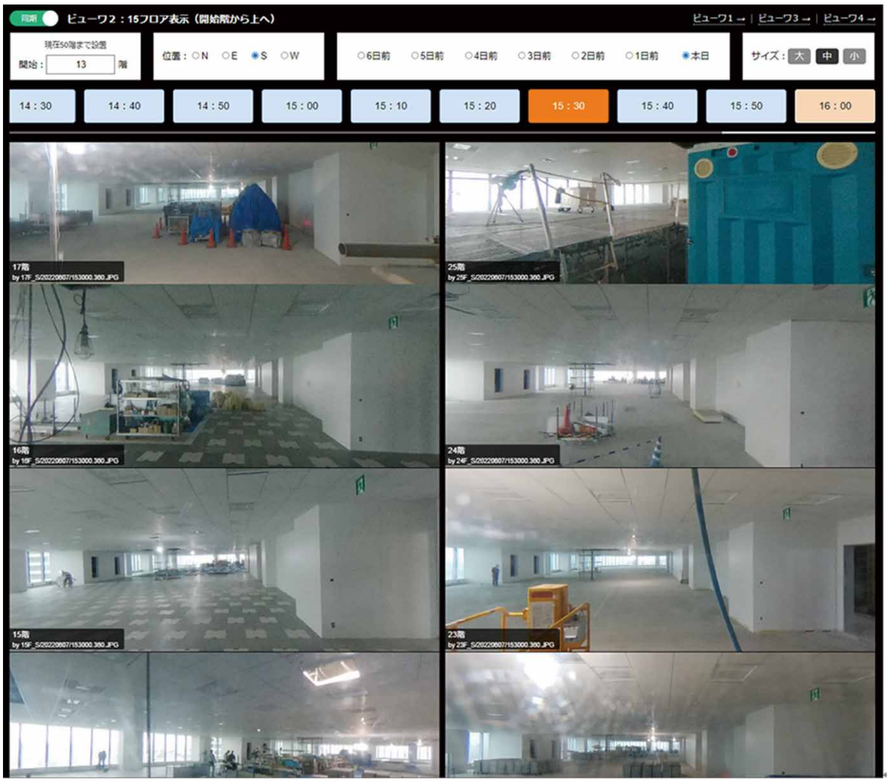
It was used on two floors for 325 m^2 spray area and maximum spraying thickness was 45 mm.

—Robo-Buddy OA Floor

Photo 8 shows the OA floor installation robot. The robot that transports the panels and the robot that installs them work together to proceed with the installation. First, the arm on the left side sees the

Photo 5 Robo-Welder

Figure 10 Fixed Point 360-degree Camera Viewing App.



① Before welding

② Pre-heating

③ Clean weld (protection) removal

④ Pre-weld groove condition

⑤ Start welding

⑥ Complete welding

Photo 6 Welding procedure

Photo 7 Robo-Spray

Photo 8 Robo-Buddy

floor markings and sets the support legs. At this time, it receives the laser beam and automatically sets the height. Next, the right arm places the panels. Because of the robot's size, workers set up the panels near walls and other inaccessible areas, but the robot sets up most of the floor. The daily installation capacity was approximately 40 m^2, and approximately 420 m^2 of installation was successfully completed.

BIM Utilization

• BIM Linkage between Building Frame Works and Equipment

The structural framework drawings were created using Revit. Fig.11 shows that Rebro was used for coordinating with MEP systems, including verifying underground utility routes and conducting detailed inspections of steel sleeves.

KAP is a specialized CAD system for steel fabrication and used to estimate the weight of steel frames and draw general drawings of steel frames. As shown in Fig. 12, the 3D model generated at the same time as the drawings could also be used for building equipment studies.

• BIM as a "Common Language" in Complicated Geometry

In this project, it was necessary to discuss complex shapes due to wide variety of curved surfaces with many parties, including overseas designers. In this situation, we utilized BIM as a communication tool to convey visual information to all parties. This was particularly effective in the discussion of the exterior and steel frame attachments, as shown in Fig. 13.

Fig. 14 shows the large glass canopy penetrating exterior curtain wall. Canopy size is 81 m wide and 25 m deep, with a three-dimensional raised tip, and the steel frame suspended from three pillars.

BIM model shown in Fig. 15 was created by superimposing KAP, facade and canopy data on the skeleton model issued by designer. It was effectively used in design meetings.

As shown in Fig 16, this 3D model was also used for product inspection. Until now, only steel tape and inserts had been used for measurement, but by using a 3D measuring device to measure the actual coordinates of the parts and automatically plot them on the pre-input model using a PC, the model was generated on the PC in a few seconds and the dimensions could be checked. It enabled

Figure 11 Verification of Rational Routes for Underground Facilities by Rebro

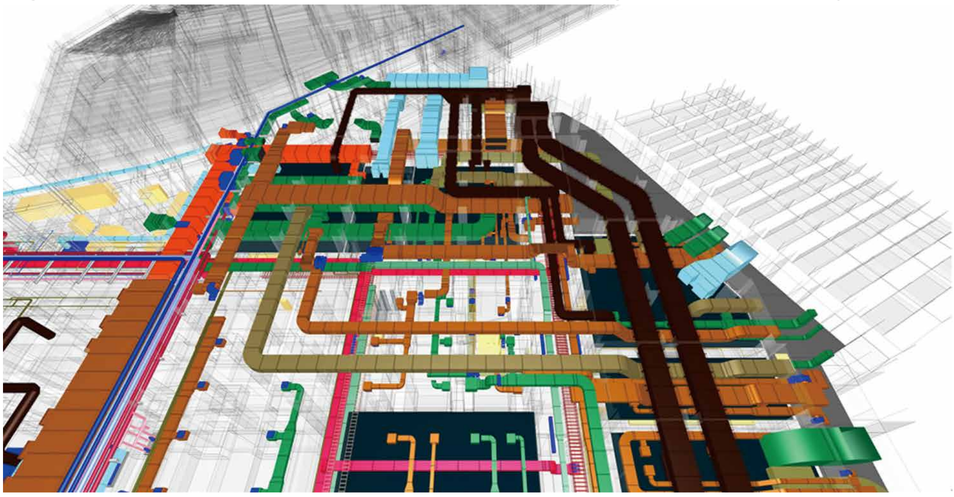


Figure 12 Steel Frame 3D Model by KAP

Figure 13 BIM Utilization

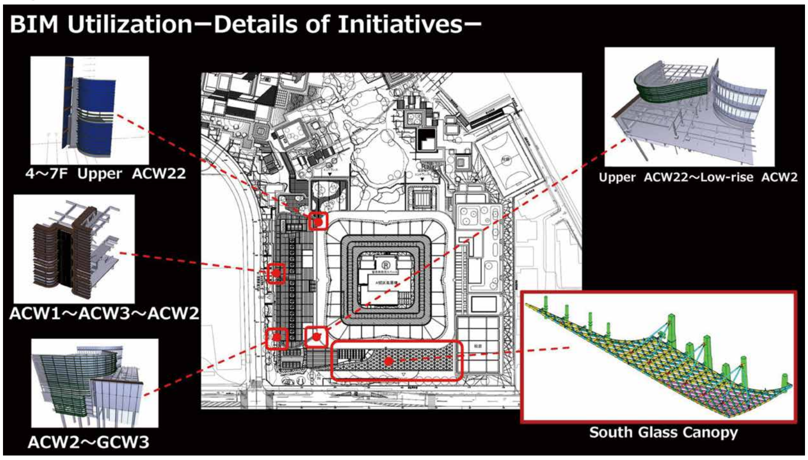


Figure 14 South Glass Canopy

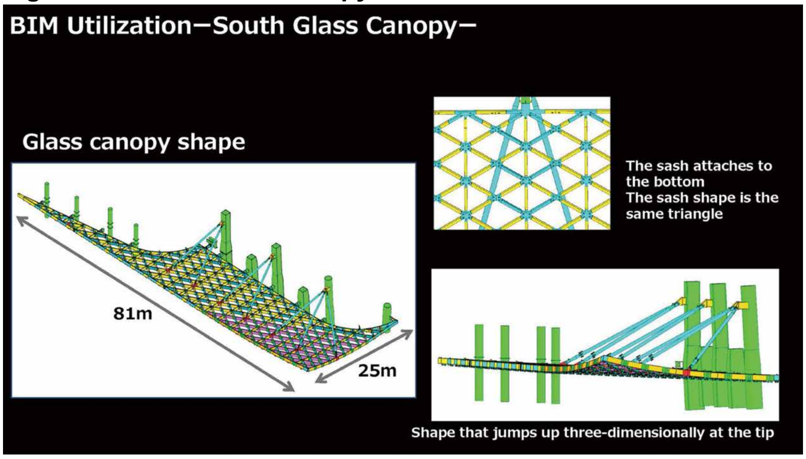


Figure 15 Superimposed Data

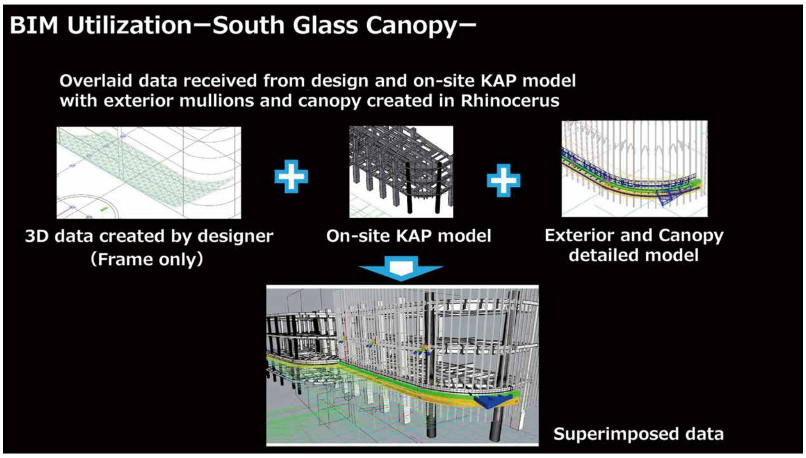
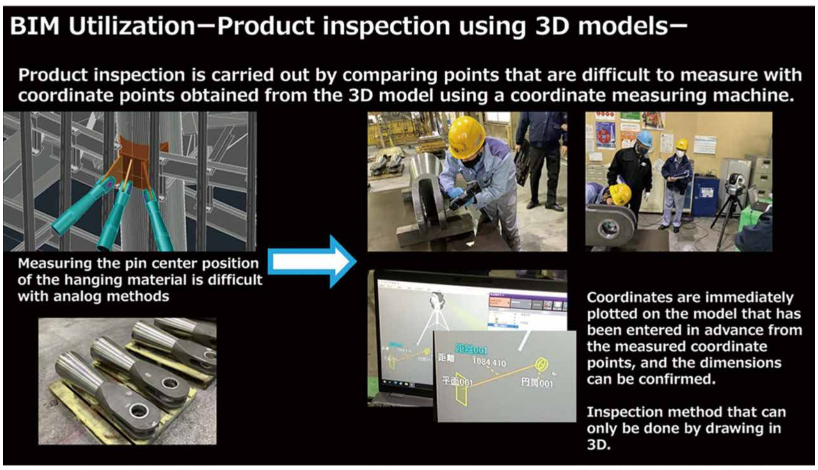


Figure 16 Product Inspection Using 3D Models



very quick and accurate inspection.

Conclusions

This article describes the DX challenges in Azabudai Hills.

As the global situation becomes increasingly severe, with climate change, pandemics, conflicts and prices escalation, Japanese construction industry is also under pressure to make major changes.

The DX challenge in this project is just the first step, but we must continue to take on the challenge to solve the issues listed below and meet further demands.

(1) Standardization of tools as well as standardization of working procedure is needed.
(2) Advanced analysis and next actions are needed for big data obtained through improved sensing technology and advances in communications and software.
(3) Rather than aiming for full automation, it is important for engineers to use robots to improve productivity, and developers need to fully understand the work in the field and aim for optimal work sharing between humans and robots.
(4) Standardization of tools and drawing work is needed for further utilization of BIM.
(5) In order to deploy DX to many sites, it is necessary to reduce costs and lower the hurdles to trial.
(6) Even if the results of a new initiative do not reach the desired level, the data obtained from it should be used for the next development and continue to grow.

Acknowledgments
Construction of the A Block was completed in June 2023. We would like to express our sincere appreciation to all parties involved in this project.

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Research and Development in Japan —Electroslag Welding Applications for Steel Building Construction—

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Introduction

Electroslag welding (ESW) was originally developed in the Soviet Union in 1951, initially as an efficient vertical welding method[2) 3)] as shown in Figure 1. ESW could significantly improve the efficiency of welding thick steel plates.

The ESW method has various advantages over general arc welding, including single-pass welding for thick plates, superior workability, and simpler bevel preparation. However, owing to the high welding heat input, the ESW has a disadvantage that the crystal grains of the weld metal and heat-affected zone (HAZ) tend to be coarsened, making it difficult to obtain high toughness, which may be a serious problem in steel structures, particularly in seismic applications.

In Japan, using ESW to install inner diaphragm plates in welded built-up box columns for the construction of high-rise steel buildings is a common practice. This article aims to present state-of-the-art research and development on ESW applications in steel building structures in Japan. A history of ESW technology development is first presented (Table 1), and then the essence of a design recommendation on ESW welding of inner diaphragm plates[4) 5)] is introduced.

Figure 1 Schematic of the Earliest ESW (adapted from Ref. 2)

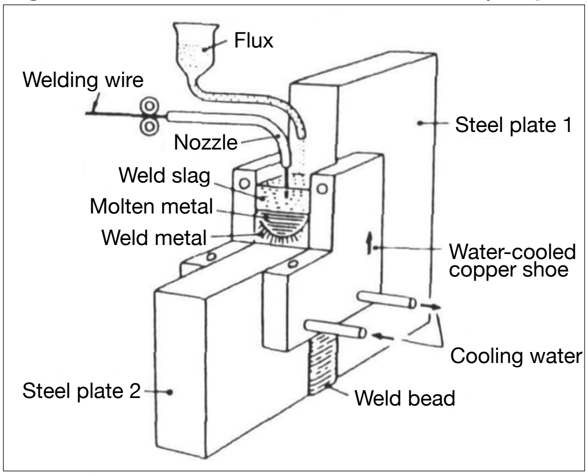


Table 1 Timeline of ESW Development for Building Structures in Japan

1951	ESW was developed in the Soviet Union
1965	First ESW application to shipbuilding at Kawasaki Heavy Industry in Japan
1968	Kasumigaseki Building completed; the first full-fledged application of ESW to steel building structures in Japan
1970-1971	Two-sided ESW for weld box column was developed
1971	Four-sided ESW for weld box column was developed
1971	“Specification of Consumable ESW” published by Architectural Institute of Japan
1990s	Simplified non-consumable ESW was developed
1995	Hyogo-ken Nanbu Earthquake
2016	“Guide on Preventing Brittle Fracture of Inner Diaphragm Plate Electroslag Welds” published by Japanese Society of Steel Construction
2025	“Guide on Preventing Brittle Fracture of Inner Diaphragm Plate Electroslag Welds” (English version) published

Note to “Electroslag Welding Applications for Steel Building Construction”
This article is a condensed adaptation of the following previously-published article, to which recent advancements in Japanese R&D have been added:

- Yukihiro Harada, Jun Iyama, Yuka Matsumoto, Kazuaki Suzuki, and Koji Oki: “Electroslag Welding Applications for Steel Building Construction in Japan: A State-of-the-Art Review,” Engineering Journal, Vol. 60, No. 2, pp. 93-110, Q2 2023

Development of ESW for Steel Building Structures in Japan

• The Beginning of ESW Application to Building Steel

In 1964, a simplified ESW method with a consumable nozzle and fixed cooling plates was developed and implemented by several Japanese companies, as shown in Figure 2[6]. The consumable nozzle melts and gets consumed as the welding progresses.

The simplified consumable ESW was first used in 1965 for the construction of steel building beam-to-column connections. In the Kasumigaseki Building in Tokyo, which was completed in 1968 and is recognized as the first high-rise building in Japan, the ESW was adopted to build the steel frameworks.

In the 1960s, wide flange (H section) shapes were widely used for columns in high-rise steel buildings because a wide flange steel was less expensive than a box section. However, structural designers considered the box section to be structurally more efficient than the wide flange shape. A disadvantage of using box-section columns was that they were labor-intensive and expensive, particularly when fabricating beam-to-column joints with inner diaphragm plates.

This situation changed after ESW was introduced to weld inner diaphragms in built-up box columns in the 1960s, which significantly reduced the fabrication cost, especially for columns with thicker plates. With this method, face plates of the column could be made continuous without the need to cut and re-weld. Since then, shop-welded built-up box columns with ESW have been widely used for high-rise steel building construction in Japan.

During the 1970s and 1980s, various box column fabrication methods utilizing ESW, including two-sided ESW, were applied. Since then, the four-sided ESW method has been a standard practice for welding inner diaphragm plates in built-up box columns, as shown in Figure 3[7].

• Development of Simplified Non-Consumable ESW

As the consumable ESW had been widely applied in fabricating built-up box columns for high-rise construction, the disadvantage of the consumable ESW due to its high-heat input had become recognized.

One of the solutions to avoid these defects was to develop a highly efficient welding method with a reduced heat input. A simplified non-consumable ESW method with an elevating nozzle was developed by Nippon Steel Corporation[8] to address the problem in the 1980s, as shown in Figure 4. The welding process is called by its trade name ("simplified electroslag welding process with non-consumable elevating tip") and has been applied to almost all diaphragm welding of box columns in Japan.

Figure 2 Schematic of Simplified Consumable ESW (adapted from Ref. 2)

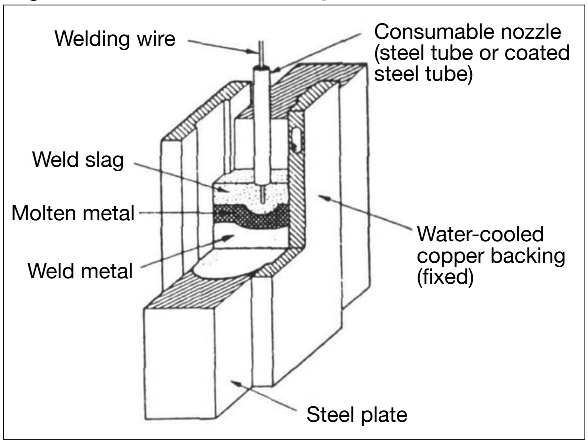


Figure 3 Four-sided ESW Method in Current Practices (adapted from Ref. 7)

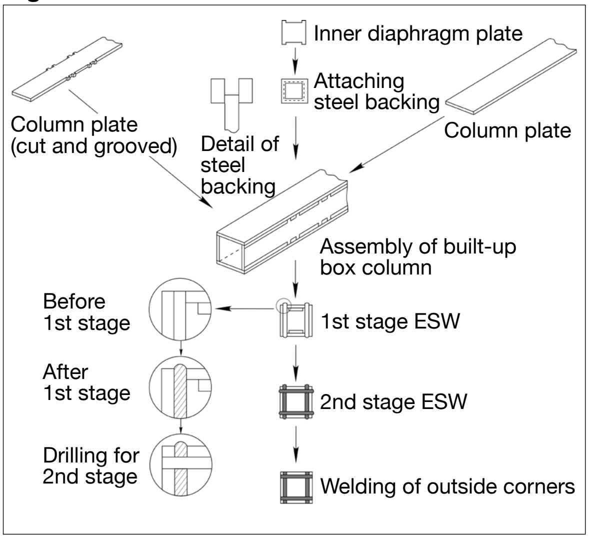
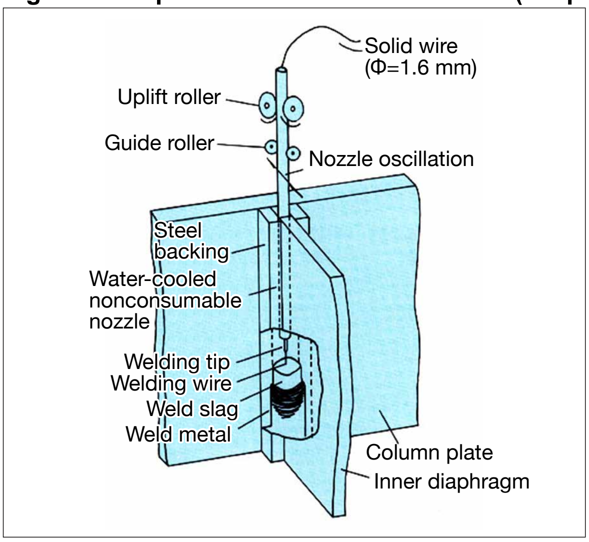


Figure 4 Simplified Non-consumable ESW (adapted from Ref. 8)



Recommendations for Brittle Fracture Prevention of Inner Diaphragm Electroslag Welds

• Background of the Publication of the Recommendation

The Hyogo-ken Nanbu Earthquake in 1995 caused significant damage to steel structures in Japan. The typical fracture involved a crack initiating from the beam flange weld in through-diaphragm type beam-to-column connections, as shown in Figure 5(a). No damage was reported on the ESW joint in welded box columns, as shown in Figure 5(b). However, later dynamic loading tests revealed that brittle fractures could initiate from the slit tip of the ESW joint in the inner diaphragm of built-up box columns, as shown in Figures 6 and 7[10]. This led to coordinated research in Japan on fracture prevention for ESW joints, particularly with 490 N/mm^2 class steel[11]. The Japanese Society of Steel Construction (JSSC) published the "*Guide on Preventing Brittle Fracture of Inner Diaphragm Electroslag Welds*" in 2016[4], with an English version released in 2025[5].

• Fundamental Idea of Fracture Prevention of ESW Joint at the Inner Diaphragm

Shimokawa et al.[12] summarized the experimental results of a series of loading tests. Figure 8 shows an example of the observations from the testing of three beam-to-built-up box column subassemblage specimens. In the example, if the Charpy V-notch (CVN) value, ${}_vE$, at the HAZ, fusion zone (F.L.), or weld metal (W.M.) of the ESW joint was lower, brittle fracture would occur, and both the ultimate strength and ductility were smaller. A series of experiments confirmed two key findings: brittle fracture originated from crack initiation and propagation at the slit tip of the ESW joint, and a positive correlation was observed between the nominal tensile stress acting on the ESW joint and the toughness of the brittle fracture zone.

Figure 9 shows a schematic of the tensile forces acting on the ESW joint. The tensile force on the inner diaphragm, P_d, is determined by the forces on the beam flange and web. P_d primarily drives the force P_{req}, which can tear the slit tip in the HAZ of the ESW joint. To prevent brittle fracture, P_d (or the nominal tensile stress ${}_d\sigma$ at the critical cross-section of the ESW joint) must be kept low. The *Guide* provides a procedure to evaluate fracture risk at the ESW joint, limit-

Figure 5 Types of Beam-to-Box Column Joints (adapted from Ref. 9)

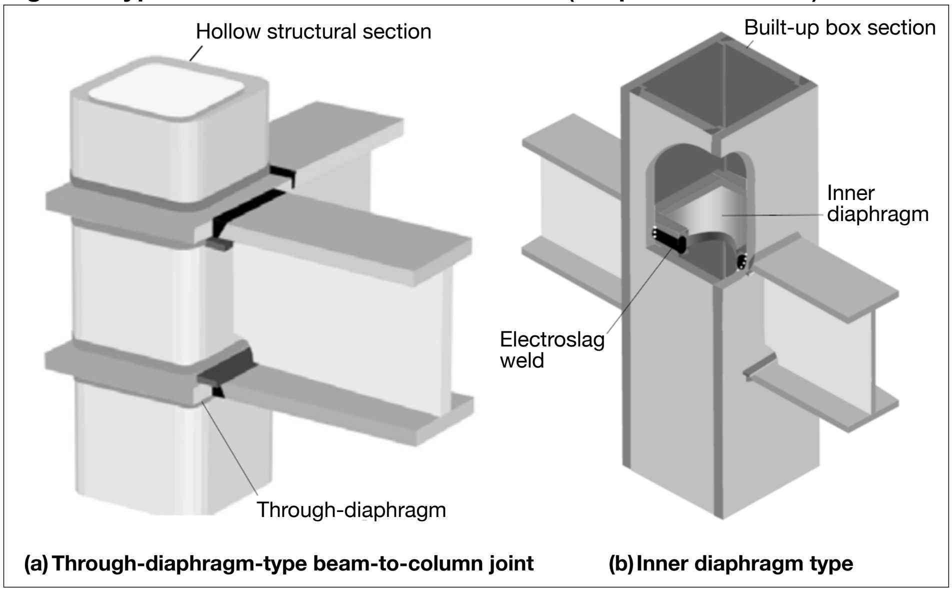


Figure 6 Example of Subassemblage Specimen with Fractured ESW at the Inner Diaphragm (unit: mm) (adapted from Ref. 10)

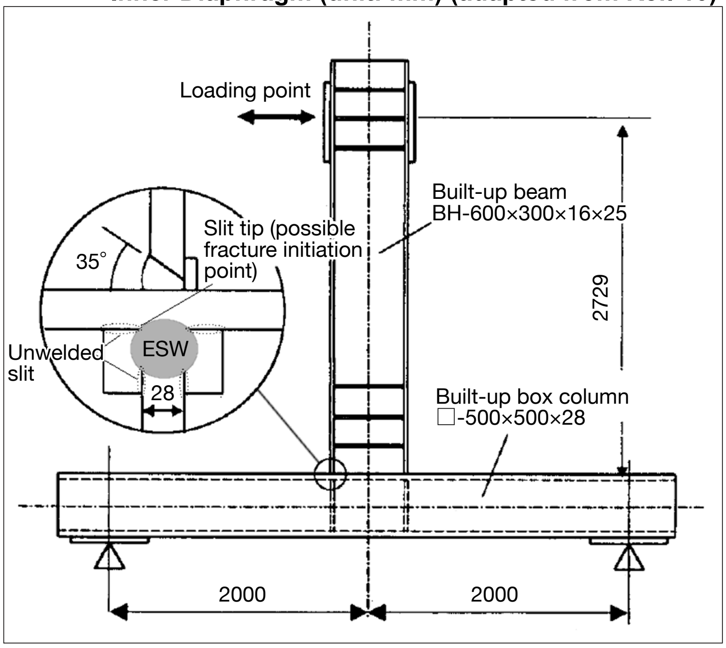


Figure 7 Example of ESW Joint Fracture in Beam-to-Box Column Subassemblage Loading Tests (adapted from Ref. 5)

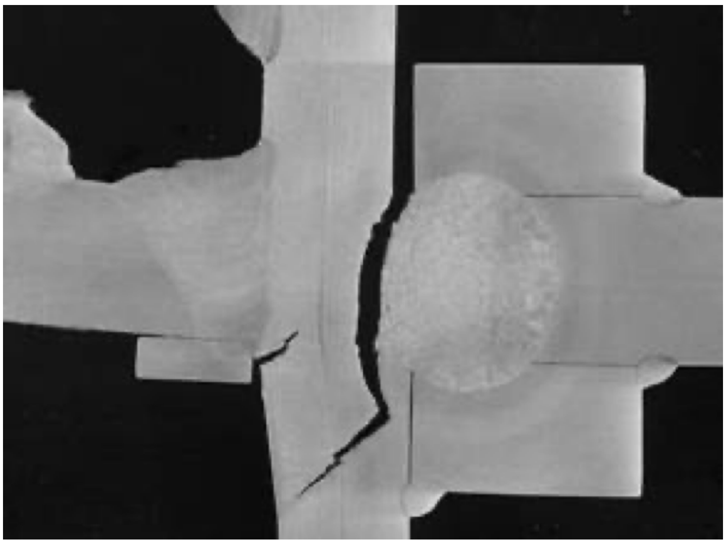
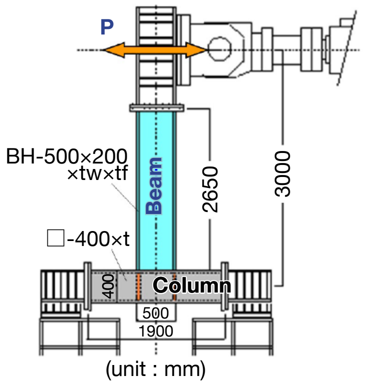


Figure 8 Example Results of Beam-to-Built-up Box Column Subassemblage Loading Tests (adapted from Ref. 12)

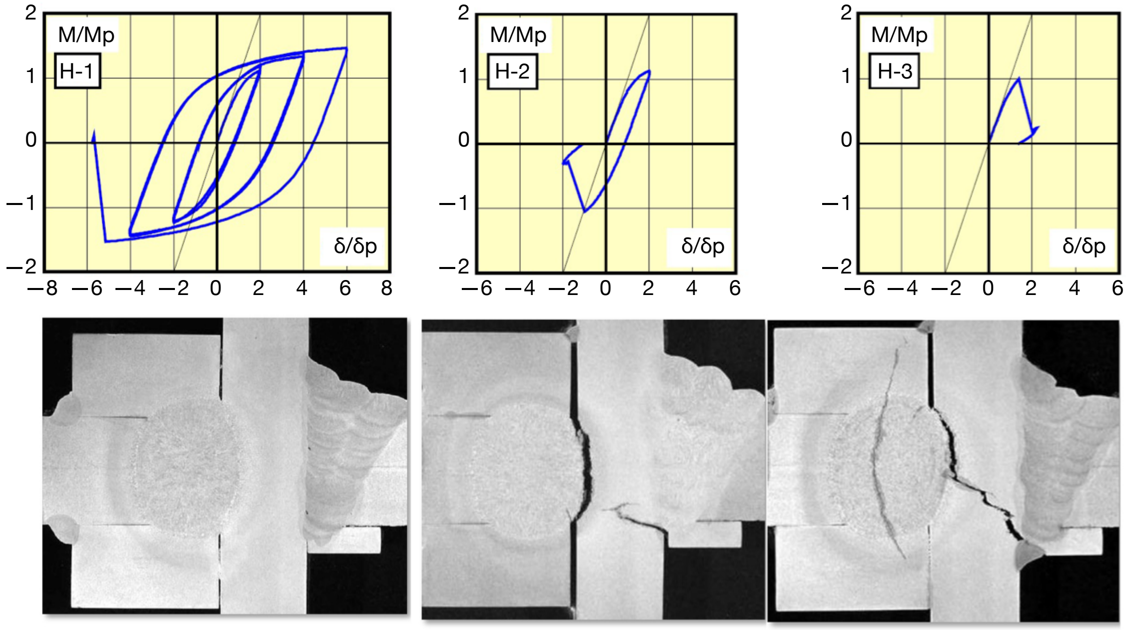


No.	Column: Section	Column: Steel	Beam section	Test temp.
H-1	□-400×28	High toughness SN490C	SN490B BH-500×200×22×40	−20°C
H-2				−40°C
H-3				−40°C

No.	Column	Test temp.	HAZ: $_vE$ (J)	HAZ: B (%)	F.L.: $_vE$ (J)	F.L.: B (%)	W.M.: $_vE$ (J)	W.M.: B (%)
H-1	High toughness SN490C	−20°C	74	72	75	77	69	73
H-2		−40°C	29	91	14	97	44	82
H-3		−40°C	19	94	18	93	14	92

(B : Percent brittle fracture)

(a) Outline of the subassemblage tests



(b) Specimen H-1 **(c) Specimen H-2** **(d) Specimen H-3**

ing the nominal tensile stress to a threshold value dependent on the joint's CVN toughness, as shown in Figure 10.

Figure 11 shows the relationship between the ultimate strength of the ESW joints (in biaxial tensile tests and subassemblage loading tests) and the CVN toughness (at the zone where the brittle fracture initiated in the ESW joint). Each data point corresponds to a single test in which the brittle fracture occurred at the ESW joint. In this figure, the ultimate strengths of the joints P_u were normalized by the nominal yield strengths of the ESW joint, $_dP_y$. The nominal yield strength $_dP_y$ is defined as the product of the yield stress of the inner diaphragm and the effective cross-sectional area of the ESW joint, considering the penetration of ESW and the spread of the tensile stress as shown in Figure 12(a); the penetration depth notably affects the strength and deformation capacity of the subassemblage with ESW joints[13]. For the results of beam-to-column subassemblage

Figure 9 Model of Tensile Forces Applied to an Electroslag Weld (adapted from Ref. 5)

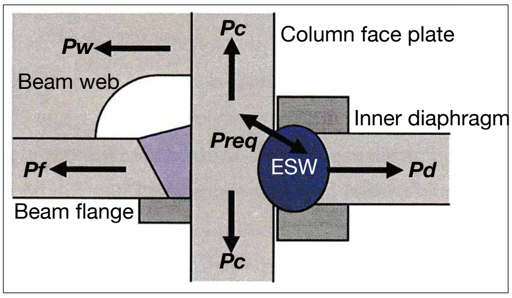
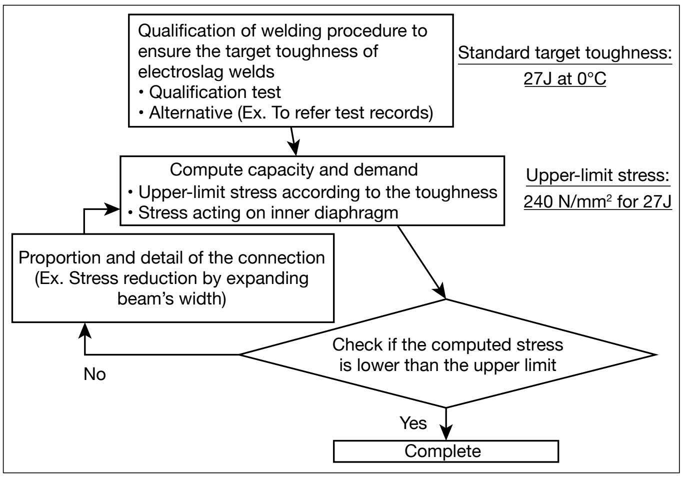


Figure 10 Procedure of Fracture Prevention Design of ESW Joints at Inner Diaphragm (adapted from Ref. 5)



tests (Figure 12(b)), the nominal stress ${}_d\sigma$ corresponding to the ultimate strength P_u of the ESW joint is derived as follows,

$$ {}_d\sigma = \frac{{}_{cf}M}{\left({}_dt+\Delta t\right)\cdot\left({}_bH-{}_{bf}t\right)\cdot\left({}_bB+2\ {}_st\right)} $$

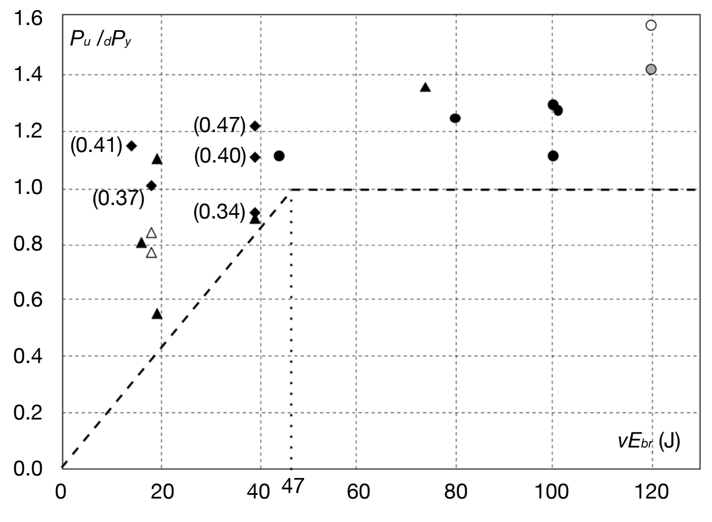
where ${}_{cf}M$: bending moment on a column face transferred from beam, ${}_dt$: inner diaphragm thickness, Δt: sum of fusion width on both sides of the inner diaphragm, ${}_bH$: beam depth, ${}_{bf}t$: beam flange thickness, ${}_bB$: beam flange width at column face, and ${}_st$: column face plate thickness.

In Figure 11, it can be seen that the fracture resistance increases as the CVN value increases. In the figure, the lower bound of the ${}_vE$–$P_u/{}_dP_y$ relationship is roughly represented by a bilinear curve consisting of two parts. The boundary between the two parts is ${}_vE$ = 47J, which means that the ESW joint will be expected to fully exert its yield strength if ${}_vE$ exceeds 47J.

In the *Guide*, the limiting values for the nominal tensile stress are listed in Table 2 as a simpler representation of the bilinear curve in Figure 11. As shown in the table, the toughness level of 15J is specified as the minimum requirement, whereas the next level of 27J is considered the de facto standard toughness level in Japan. The highest level of 47J is specified as the required toughness for the inner diaphragm to attain its yield stress without experiencing brittle fracture at the ESW joint.

Table 2 does not incorporate the effect of the axial tensile stress in the column plate on the ESW joint strength. To explicitly consider the effect of the tensile stress, the detailed assessment procedure is presented in the *Guide*; refer to the *Guide* for details.

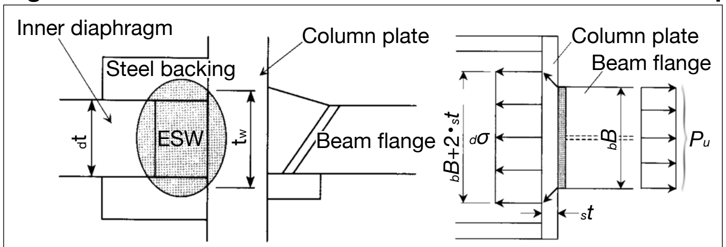
Figure 11 Maximum Tensile Resistance versus Charpy Impact Energy (adapted from Ref. 5)



Location of crack initiation	Biaxial tensile test: Tensile stress ratio 0	0.3	0.6	Subassemblage test
Deposited metal	○	● (grey)	●	-
HAZ	△	-	▲	(#)◆

: The tensile stress ratio corresponding to the nominal tensile stress due to bending moment at the experimental ultimate strength

Figure 12 Maximum Nominal Tensile Stress in the Inner Diaphragm



(a) Definition of effective cross-sectional area (adapted from Ref. 5)

(b) Definition of beam-to-column subassembly dimensions

Table 2 Criteria for the Upper Limit of Tensile Stress Acting on the Inner Diaphragm (adapted from Ref. 5)

Toughness level at an electroslag weld vE	15J or higher	27J or higher	47J or higher
Upper limit of tensile stress ${}_d\sigma$	160 N/mm^2 (0.5×F)	240 N/mm^2 (0.75×F)	325 N/mm^2 (1.0×F)

F: Design standard strength, F=325 N/mm^2 for 490 N.mm^2-class steel

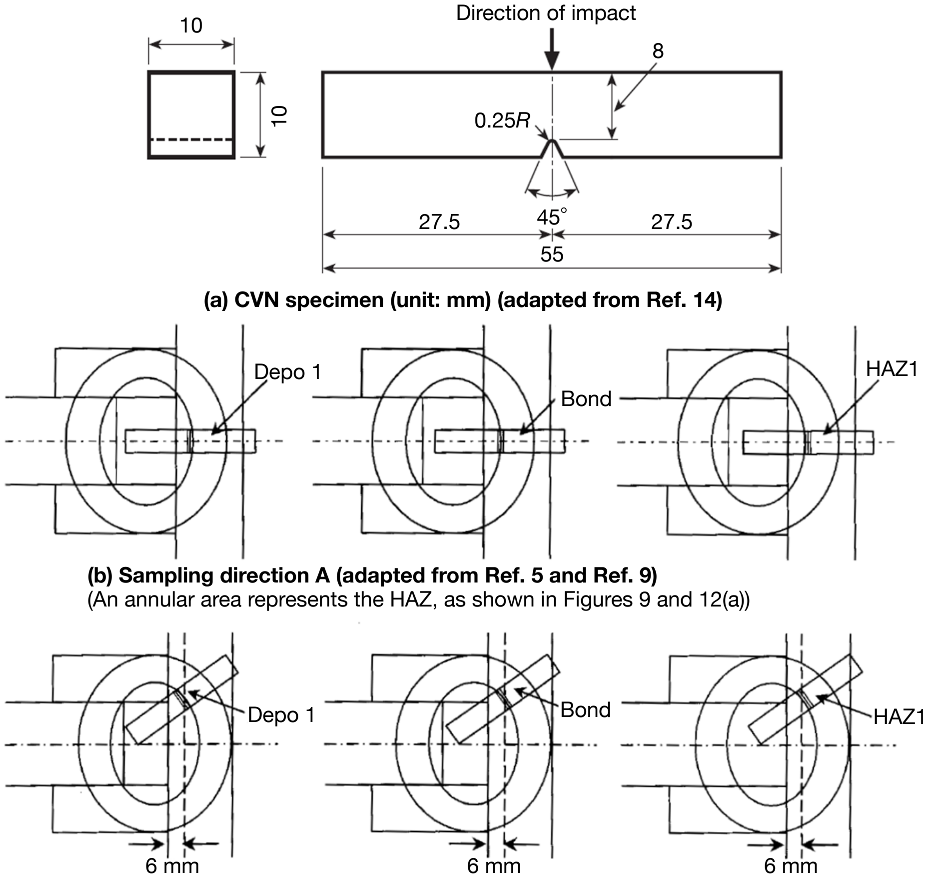
• Weld Testing Method for ESW at the Inner Diaphragm

To examine the risk of brittle fracture of an ESW joint, it is necessary to evaluate the toughness of the ESW joint. The *Guide* provides a clear procedure to sample CVN specimens in order to determine the toughness of the ESW joint.

For each ESW joint, V-notch specimens (Figure 13(a)) are sampled from three positions: the bottom of the V-notch on the bond zone (Bond), 1 mm toward the weld metal from the bond (Depo1), or 1 mm toward the base metal from the bond (HAZ1) as shown in Figure 13(b) or (c). Three V-notch specimens at each notch position are required for a total of nine specimens. At each position, the average CVN value is calculated from three specimens, and the lowest average CVN value from Depo1, Bond, and HAZ1 represents the toughness of the ESW joint.

The Charpy V-notch specimens are collected such that the centerline of the inner diaphragm aligns with the centerline of the V-notch specimen, as shown in Figure 13(b). This is called a sampling direction A in the *Guide*. This sampling method is relatively easy to position and to cut out the V-notch specimen. Therefore, this type of sampling has been widely adopted. However, the toughness of the ESW joint cannot be adequately evaluated if the ESW penetration into the column plate is significant.

Figure 13 Collection Position of Charpy V-notch Test Specimens



(a) CVN specimen (unit: mm) (adapted from Ref. 14)

(b) Sampling direction A (adapted from Ref. 5 and Ref. 9)
(An annular area represents the HAZ, as shown in Figures 9 and 12(a))

(c) Sampling direction B (adapted from Ref. 5 and Ref. 9)

In addition to conventional sampling direction A, to address the potential limitation of the sampling direction A, a sampling direction B was introduced in the *Guide*, as shown in Figure 13(c). As shown in Figure 13(c), the specimen is oriented at the position where the V-notch is at or near the intersection between the line of the ESW joint and a line 6 mm away from the back surface of the column plate. The choice of the sampling type depends on the extent to which the fusion line of the ESW joint is close to the mid-thickness of the column plate. In a recent manual for the mechanical test of weldment in steel building structures[9], the sampling direction B is adopted as the standard sampling method.

Current and Future Developments

The *Guide* is intended for the 490 N/mm^2 class of steel column plates, and the research challenge is to expand the application to high-performance steel. For example, a series of experimental studies on the ESW of SA440C steel, whose tensile stress is higher than 590 N/mm^2, was conducted[15) 16)], which validates the assessment methods in the *Guide* with a slight modification for higher-strength steels. Studies on the 780 N/mm^2 class steel are currently underway.

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POWERX FACTORY PROJECT

—Remodeling of Large-scale Existing Factory into Column-free Bright Space by Utilizing Existing Steel Framings—

Kazuyo Sejima & Associates

A primary objective of the "POWERX FACTORY PROJECT" being promoted by PowerX, Inc. is to remodel an existing factory into a new factory that manufactures large-scale battery energy storage systems. Specifically, capitalizing on the application of steel framings of the existing factory building just as they are, the existing factory was remodeled into a new refined factory with a large space of 45 m × 140 m over which a large truss roof spans. It is located near the Uno Port of Tamano City in Okayama Prefecture.

A natural light-rich bright space has been realized by providing not only top lights arranged in a slit state over the entire ceiling but also the glass sashes newly-installed at the lower section of the external wall.

Working Place Where Factory and Office Are Integrated

In order to develop its operation of large-scale energy storage systems with the aim of the wide-spread use of renewable energy, PowerX, Inc. has worked out the "POWERX FACTORY PROJECT" that aims at realizing a new type of working place where factory, office and research laboratory are integrated.

The following two conditions served as the deciding factors for the promotion of this new project. Firstly, the factory remodeling site is close to the port so that the product manufactured at the new factory can be transported worldwide by ship. Further, cherishing nature and culture, the remodeling is to be undertaken at a site that is also close to Naoshima, an island in the Seto Inland Sea that is known for its contemporary arts.

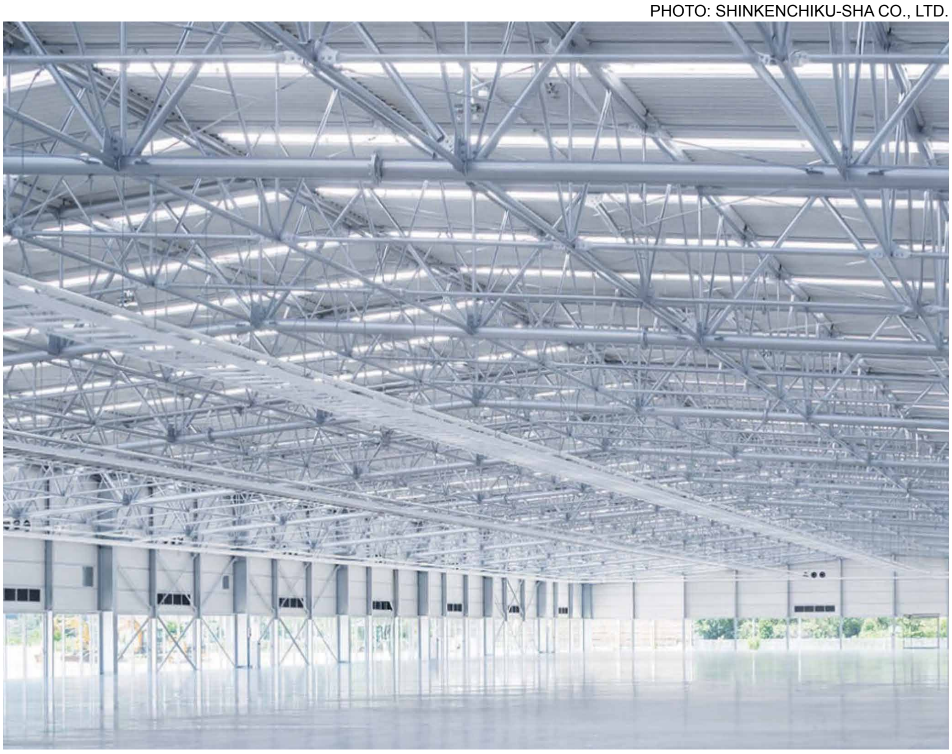
The current project is positioned as a new operation for PowerX, Inc. Therefore, in order to put the new factory into operation as soon as possible, the company has worked out a plan whereby the new factory is built by means of the remodeling of existing factories on a site where the building to be used as the new factory has already been built, and where the new office building can also be built.

On the project site that extends to about 28,000 m^2, four old factories were originally built. While taking into account their use without demolishing as much as possible, it was finally decided to demolish two small-scale facto-

PHOTO: POWERX, INC.

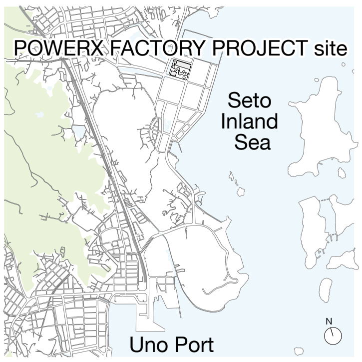
Full view of the POWERX FACTORY PROJECT site

PHOTO: SHINKENCHIKU-SHA CO., LTD.



Inside view of the remodeled factory

Location of POWERX FACTORY PROJECT



Model of Entire Project Site: Factory Building (upper) and Office/Laboratory Building Planned for Completion in 2026

PHOTO: KAZUYO SEJIMA & ASSOCIATES

1st-floor Plane Drawing

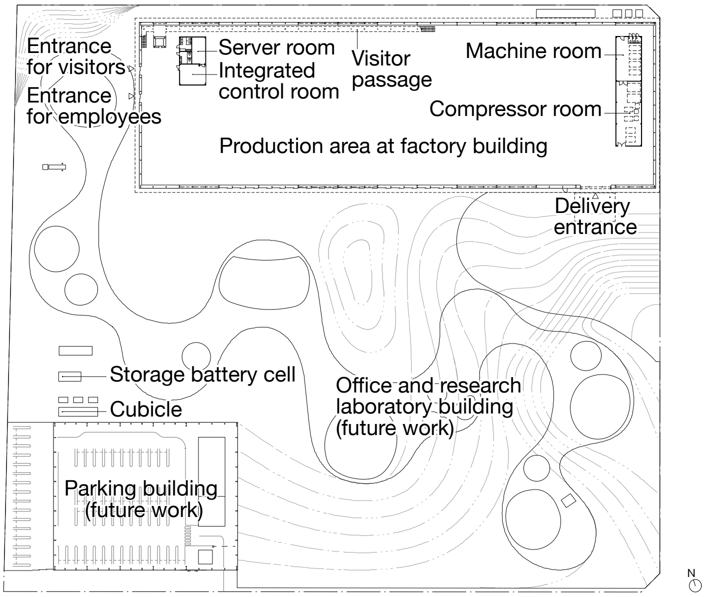
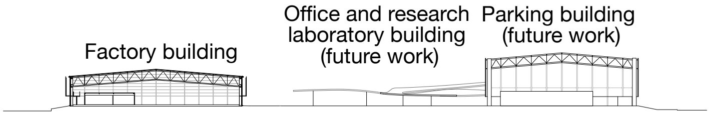


PHOTO: SHINKENCHIKU-SHA CO., LTD.

Inside view of the north side of the remodeled factory: Existing steel-frame trusses were silver-coated and a visitor passage was newly installed at the position of a wall height of 2,300 mm.

Transverse-direction Drawing



Longitudinal-direction Drawing

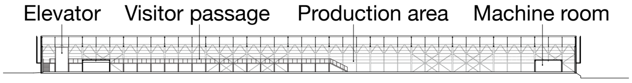


PHOTO: KAZUYO SEJIMA & ASSOCIATES

Inside view of the existing building: It was constructed in 1996 and used as a factory.

PHOTO: KAZUYO SEJIMA & ASSOCIATES

Remodeling of existing factory building: Exterior wall was removed to newly install sashes in the lower section.

ries and to install an office and research laboratory building between the two remaining factories. It was designed so that the factory and office could be integrated while at the same time preparing a layout that would allow visitors to tour the factory safely.

In the POWERX FACTORY PROJECT, the factory remodeling work started first. The design of the new office and research laboratory is almost complete. It took about one year to carry out the overall plan for the project and the design for the factory remodeling, and the factory remodeling period was seven months.

Utilizing Steel Framings in the Existing Factory

The existing factory building is composed of a column-free space measuring 45 m × 140 m, and the maintained steel-frame truss is an old but fine structure. In light of this, the remodeling plan was worked out so that part of the existing steel framings would be reinforced and the existing framing structure reused as much as possible.

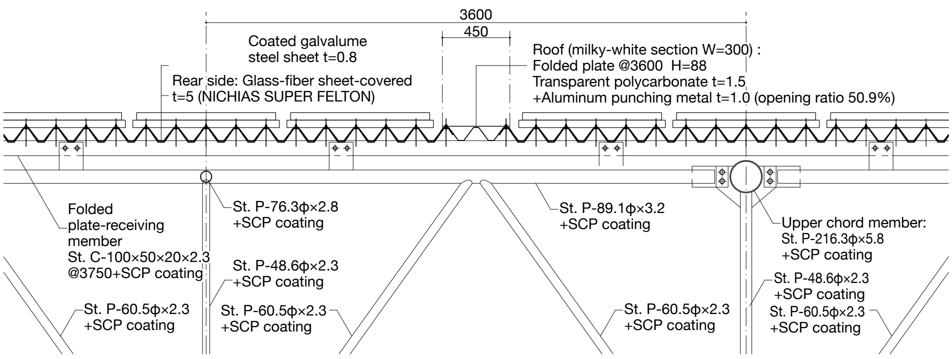
Top lights were newly provided on the roof to brighten the entire interior and sashes were arranged on the lower section of the exterior wall to allow a view of the surrounding scenery. In order to preserve the atmosphere of the old-fashioned existing factory, the same materials as those used in the existing building were adopted for the roof and exterior wall.

The truss framing of the existing building was installed in 1996, and its joint section was structurally not only very clear but also rational and nonwasteful.

Reinforcement of Steel-frame Trusses

In the remodeling work, it was decided that solar panels used as usual in the site are installed on the roof of the new factory. When these solar panels were installed on the roof of remodeled fac-

Detailed Drawing of Roof Section



tory, the weight of the roof increased, and therefore the roof truss framing was reinforced. Basically, the truss structure resists the working load with its axial force. The steel-frame member is highly resistant to the tension force, but when subjected to compressive force, it causes buckling thereby leading to the reduction of its strength.

It was learned from a structural analysis that the compressive stress occurring in part of the upper/lower chord members had surpassed the allowable compressive stress. In order to reinforce these members without replacing them, the following method was adopted—the cross section where stress surpassing the allowable stress occurs was increased to lower the compressive stress. In terms of practical reinforcement, the shape and installation position of the reinforcing members were devised so that they could not been seen from the ground level, and further flat bars with a thickness of 6 mm and a height of 80 mm were weld-joined to the round tubes of the upper/lower chord members.

The longitudinal-direction side of the existing building was composed of a brace structure, and the brace on the span to which an opening had newly been installed was moved to other spans to leave the number of braces the same.

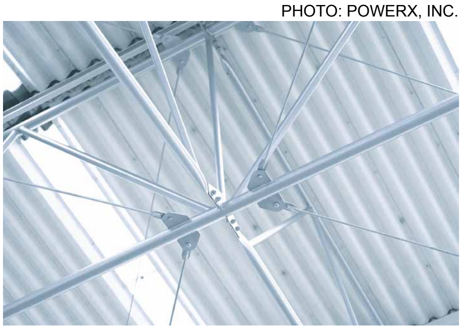
Because the moment occurring in the column increases with the increase of axial force occurring in the upper/lower chord members, the CT shape was weld-joined to the column's outer side to increase the cross-sectional performance of the columns.

The truss was originally painted yellow-green but was painted a beautiful silver color, thereby giving the whole factory a brighter look.

Brighter Interior of New Factory

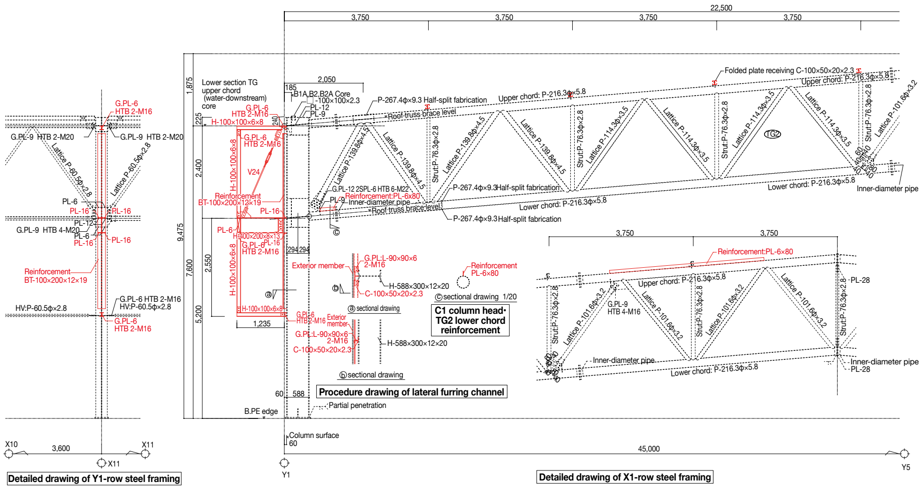
The top light was arranged on the roof. While the existing factory interior was dim because of such a vast floor area, it

PHOTO: POWERX, INC.



Existing frame structure employing slender members: Top light was arranged on the ceiling at an interval of 3.6 m

Detailed Drawing of Steel Framing (Red: Newly-installed section)



Detailed Drawing of Section

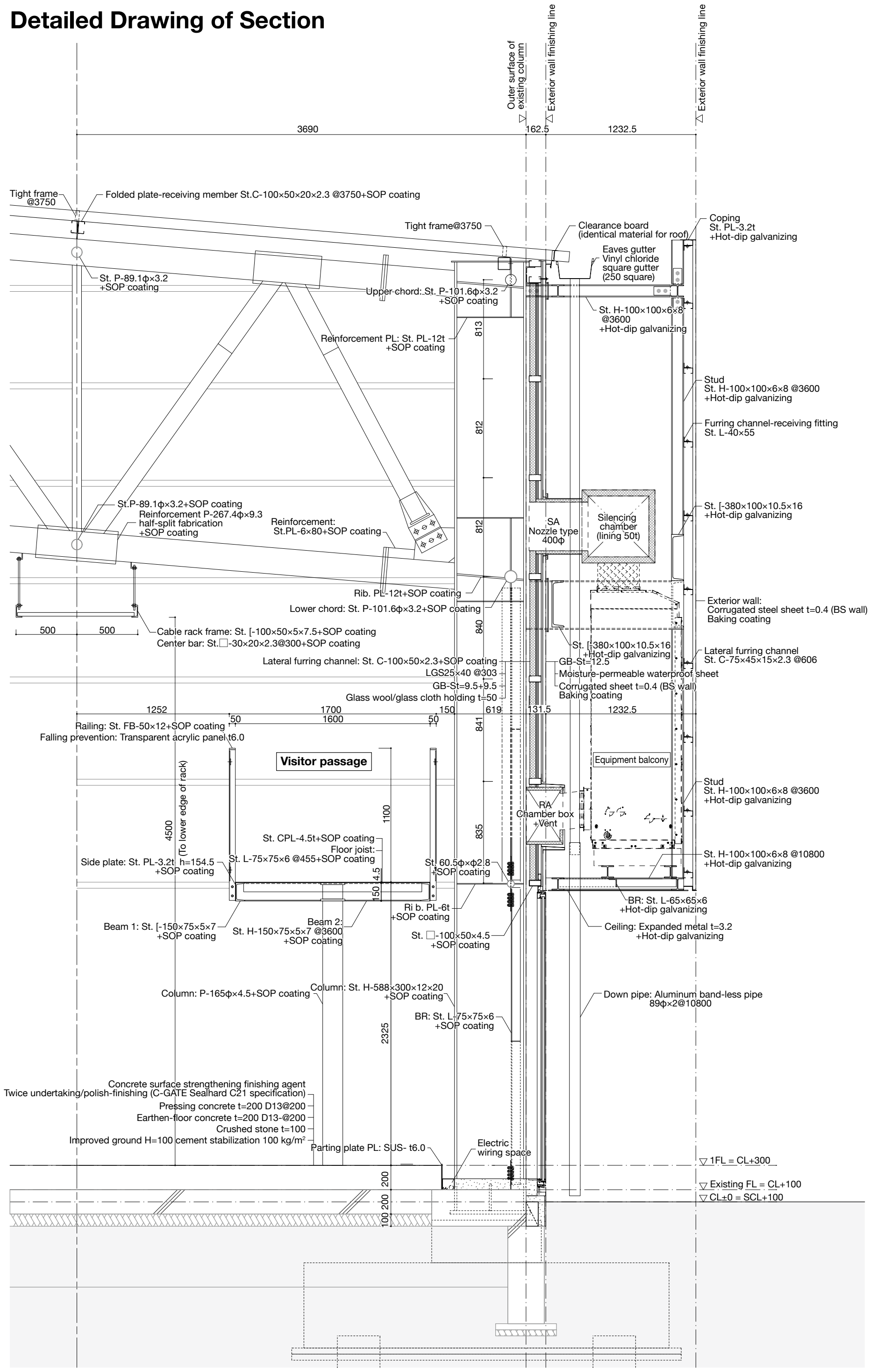


PHOTO: KAZUYO SEJIMA & ASSOCIATES

Double-skin exterior wall under construction

PHOTO: IWAN BAAN

Factory interior in which the battery energy storage manufacturing facility was prepared: Floor concrete was replaced to finish the floor flat.

was designed so that a bright new factory with natural light was completed. The roof was remodeled with a folded-plate roof (coated galvalume steel sheet) with a cross section identical to that of the existing building. It was finished with transparent polycarbonate sheets installed at an interval identical to that of the folded plates, through which the lighting was arranged.

Because the longitudinal-direction columns were installed at an interval of 3.6 m, the 450 mm-wide polycarbonate sheet was also arranged at a pitch of 3.6 m so that the top light was arranged in between the columns. The solar panels were installed on the galvalume sheet roof.

Lighting equipment was attached on the main column arranged in an interval of 10.8 m. During the daytime, the factory interior is bright enough without turning on the lights.

Changing the Four Sides of the Lower Part of the Exterior Wall to a Glass Sash Structure

The exterior wall of the existing factory was completely removed to leave only a steel-frame structure, and then this was remodeled. In the existing factory, the exterior wall was solid all the way down to the bottom, but in the remodeling, a ready-made glass sash was arranged in the 2,500 mm-high bottom section of the four sides of the factory building.

For the upper wall section, corrugated steel sheet with a section similar to that of the existing factory was adopted. On the outer side of the wall, a single-layer wall was installed to form a double-skin wall, between which indoor and outdoor air-conditioning equipment was installed. This wall arrangement of invisible air-conditioning equipment inside the factory made it possible to work out a completely open structural plan for the inside of the remodeled factory. In the installation of the additional wall, a structure was adopted in which the beam tips were suspended from the column heads by the use of braces.

The outer wall was finished with cream-colored corrugated steel sheets, the same material used in the existing factory. In the current remodeling, when heat-insulation material and sound-absorption members were inserted into the wall, it would have been easier to insert them from the wall top so as to hide the furring channel, but they were packed between furring channels. We thought that, if all furring channels were hidden in finishing the entire wall, the remodeled factory would offer an atmosphere of an office, not a factory, and as a result, the furring channel was left visible to avoid this.

New Concrete Placement on Floors

The floor surface of the remodeled factory was flattened and finely prepared. The asphalt pavement on the half area on the south side of the existing factory was removed and the concrete foundation on the half area on the north side was drilled so as to make the entire floor area flat, on which concrete was newly placed.

In order to make the difference of level between the factory outside and inside small and to further suppress the remodeling cost, the thickness of the newly-placed concrete was set at 200 mm for the half area on the south side where the automated rack warehouse was arranged and 150 mm for the half area on the north side.

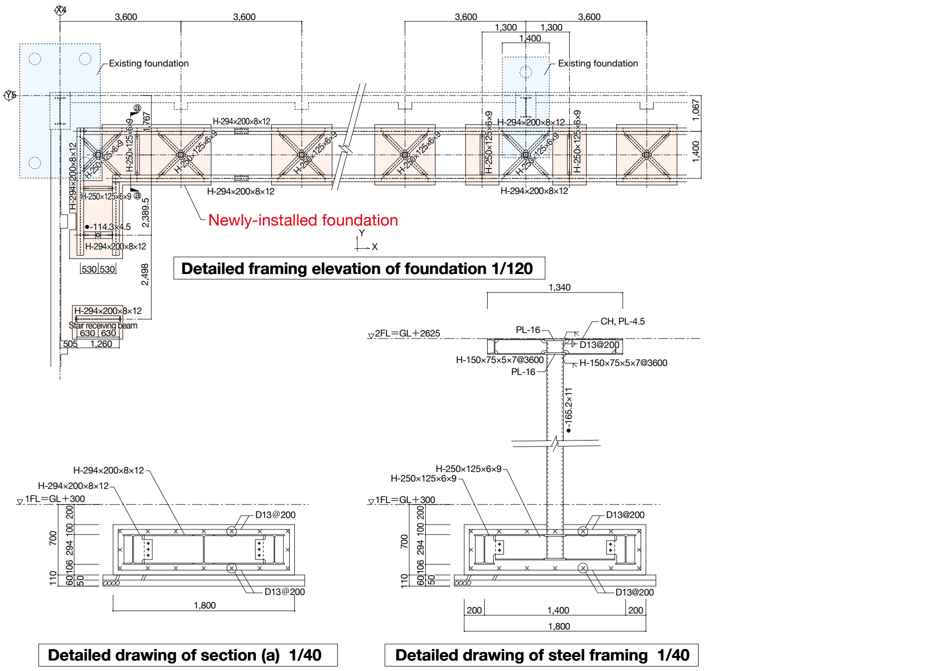
Extension Work for Visitor Passage

A visitor passage was newly installed along the wall height on the north side. At the stage of structural design, the arrangement of two-row columns was anticipated for the installation of the visitor passage. However, as a result of the preparation of the mockup and an aesthetical examination, it was decided to adopt a one-row column arrangement. In the case of adopting a two-row column arrangement, because the passage shakes up and down due to the footsteps of visitors, there are no fears in terms of structure even when the passage causes a little shaking. Instead, in the case of adopting a one-row column arrangement, the passage is liable to shake right and left due to the walking load of visitors.

In light of these forecast structural conditions, it was considered that the loading frequency for quick-pace walking was f=2 Hz (T=0.5 seconds) per step, so the one-row column section was settled so as to secure a natural frequency of f=3 Hz in the horizontal direction for the columns, 1.5 times that of the above-mentioned loading frequency.

In the existing factory building, while the main column to support the truss framing was supported employing a pile foundation, pile foundation was not applied for supporting the stud. Because the interval between the columns for the newly-installed visitor passage coincid-

Detailed Drawing of Visitor Passage



Outline of POWERX FACTORY PROJECT (Factory Remodeling)

Location: Tamano City, Okayama Prefecture
Project owner: PowerX, Inc.
Main application: Factory
Area
- Site area: 28,272.67 m²
- Building area: 8,587.09 m²
- Total floor area: 8,712.39 m²

Structure: Steel structure
No. of story: 2 stories aboveground
Maximum height: 9,785 mm
Eaves height: 9,267 mm
Architectural design: Kazuyo Sejima & Associates
Structural design: Okumura Corporation
Construction: Okumura Corporation
Design period: June-December 2022
Construction period: January-August 2023

ed with that of the existing building, it was impossible to provide a new foundation for the pile foundation position of the main columns. Therefore, the foundation for the visitor passage was newly installed in a position which differed from that of the existing foundation, and two underground beams were connected to the overall foundation. New devises were incorporated in ways that transfer the load to be borne by visitor passage columns to the ground via X-shaped underground beams at the column edge and two underground beams. Incidentally, the diameter of these newly-installed columns measured 165 mm.

While the visitor passage was a newly-installed structure, capitalizing on new devises in the current remodeling, it was possible to bring about a structural image that looks like the visitor passage is hung or placed on the floor without giving a feeling of incompatibility.

Serving as a Base for Industry and Culture

At the stage of the ongoing design of the POWERX FACTORY PROJECT, its scale is growing and there are various new discussions such as whether another existing factory building should be put into operation as a new factory. Design work is proceeding with how to make successful use of existing buildings while making use of their fine building structures and what kind of reinforcement measures should be applied to existing buildings. In the ongoing project, two existing buildings will be remodeled into a new factory, where an office and research laboratory are planned to be located. In addition, plans call for the installation of a restaurant for visitors and a rest station for employees in the new office and research laboratory building.

From the second floor of the conference room of the new factory, Naoshima, an island of contemporary arts, can be seen and an extensive view of Seto Inland Sea can also be commanded. Uno Port located near the new factory is where ships depart from Honshu Island to the Seto Inland Sea, and many people still visit Naoshima today. In the future, there may be people who will visit this factory as a link of their trip to Naoshima. We envision that such a trend will lead to round trips not only visiting this factory but also various industries and industrial heritage sites that have been in the Seto Inland Sea area since ancient times.

PHOTO: IWAN BAAN

Inside view of the factory from the newly-installed visitor passage

PHOTO: SHINKENCHIKU-SHA CO., LTD.

Evening view of the south side of the remodeled factory: Four openings with a height of 2,500 mm were arranged on the lower side of the exterior wall.

STEEL CONSTRUCTION TODAY & TOMORROW

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