The world's first steel sheet pile-based building structures -"Research Building"-

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ABSTRACT

GIKEN LTD. has completed the "Sozokan", a large-space building that utilizes steel sheet piles as the main structural members. The knowledge gained from the design and construction process of the "Sozokan" was successfully utilized in the next phase of the project. The "Research Building" was built on the site adjacent to the "Sozokan". The "Research Building", a two-story office building, was designed with the assumption that it would be used by people on a regular basis. The main feature of the building is that it is constructed with a continuous wall that integrates the functions of a pile foundation, columns, and walls by press-in steel sheet piles. This is the first case in the world to integrate the main structure and foundation structure using steel sheet piles embedded in the ground. Like the "Sozokan", the "Research Building" also uses 600mm width Hat shaped steel sheet piles (SM-J 295) that are not normally used for structural members of buildings, and has been certified by the Minister of Land, Infrastructure, Transport and Tourism after a performance evaluation by the Building Center of Japan. This paper describes the design and construction method of the "Research Building", which succeeded in maximizing the potential of steel sheet piles.

Key words: *steel sheet pile, press-in method, steel structure, 600mm width Hat shaped steel sheet piles (SM-J 295), foundation-integrated structure*

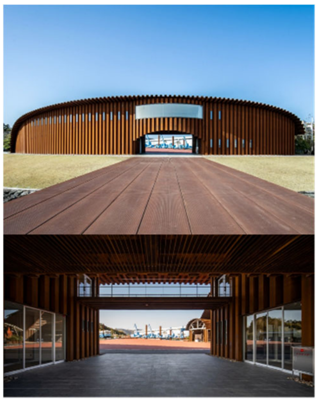
1. Outline of the project

1.1. Background and objectives of the project

GIKEN LTD. has constructed "RED HILL1967," an information transmission base for press-in technologies in Akaoka-cho, Konan City, Kochi Prefecture (**Fig. 1**). The site includes the world's first "Demonstration Area," which displays the latest " SILENT PILER™" and actual structures built by "Implant™ Method " , the "Sozokan" (The Museum of Piling Machines), which displays piling machines from around the world historical press-in machinery machines, and "Research Building" that houses a research facility, a theater hall related to press-in technology and exhibition space. This paper focuses on the "Research Building" (**Fig. 2**). The "Research Building" is the first building in the world to be constructed with a continuous wall that integrates the functions of a pile foundation, columns, and walls through the press-in of steel sheet piles.

Fig. 1 "RED HILL1967"

The press-in steel sheet piles can be used as the main structure and foundation structure as they are. The building is an architecture that makes the most of the potential of steel sheet piles. As with the "Sozokan", steel sheet piles (SM-J295), a special material, are used as the main structural members, and the building has been certified by the Minister in Japan through a performance evaluation by the Building Center of Japan. This paper describes the unique design method and construction method of the steel sheet pile structure.



Outline of the building
Site: Konan City, Kochi Prefecture
Building Use: Office
Building Area: 846.78m2
Total Floor Area: 1,110.04m2
Building height: 8.20m
Building Length: 84.0m

Structural Outline
Structure: Steel frame
(main structure is steel sheet pile)
Frame type: Ramen structure
Columns and beams: Steel sheet pile and shaped steel
Column/beam joints: High-strength bolt friction joints
Foundation type: Pile foundation
(wall and column integral)

Fig. 2 Building and Structural Outline

2. Structural design policy

2.1. Structural planning

Fig. 3 shows the structural plan of the "Research Building". Steel sheet piles are used for the second floor and R-floor roof. **Fig. 4 and Fig. 5** shows the plan and elevation. The "Research Building" consists of Zone A(31m x 12m) and Zone B(15m x 12m) two-story building connected at the center (Zone C). The height of the first floor is 4.0 m, and the height of the second floor ranges from 2.0 m to 4.0 m.

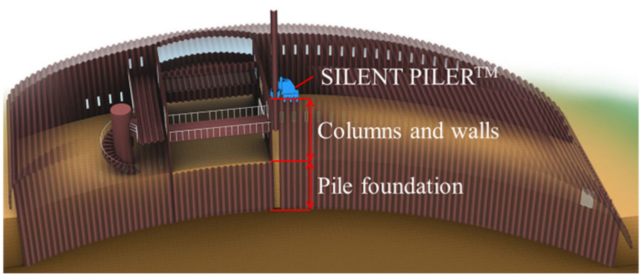


Fig. 3 Structural perspective

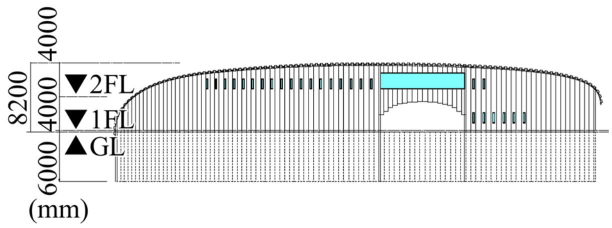


Fig. 4 Elevation

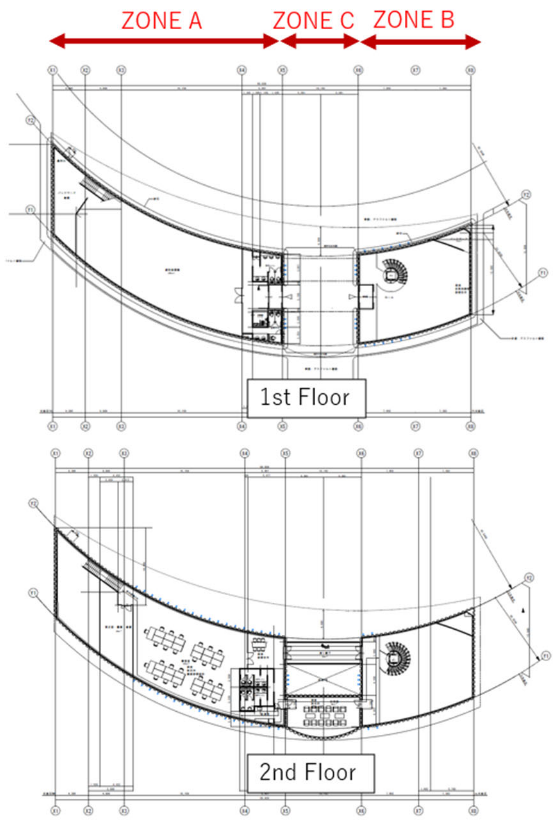


Fig. 5 Plan

2.2. Design criteria

To ensure that the components of the building will not be damaged by a major earthquake and that the deformation of the building will be limited to the extent that the exterior materials are not damaged, the design criteria were established as follows. The design criteria for the main structure are shown in **Table 1** and those for the foundation structure in **Table 2**.

Table 1. Design Criteria for Main Structure

	Mid-Scale Earthquake	Major Earthquake
Stress	Short Term Allowable Stress	Elastic Limit Capacity
Inter Story Drift Ratio	1/120 *)	—

*)It indicates the inter-story drift angle of the superstructure during a moderate earthquake. The usual requirement is to keep it within 1/200. However, for this case, in compliance with the Enforcement Order of the Building Standards Act of Japan[1)] and after confirming the safety of the exterior materials, the criteria were set to 1/120.

Table 2. Foundation Design Criteria

	Mid-Scale Earthquake	Major Earthquake
Bearing Capacity	Short Term Allowable Stress	Ultimate Bearing Capacity
Members	Short Term Allowable Stress	Elastic Limit Capacity

3. Structural analysis model overview

3.1. Modeling of steel sheet piles

Fig. 6 shows the analytical model used in the design. The steel sheet piles used for the walls and floors are 60 cm wide, so they are modeled as beam elements with nodes at 60 cm pitch. However, to increase the rigidity in the beam-to-beam direction (Y-direction), the connection between the connecting beams at X5 and X6 streets was rigidly connected. The upstairs floor and R-floor roof were pin-jointed to the connecting beams at the floor level, and the entire floor was modeled as a non-rigid floor. The distinction between pin connections and rigid connections was made in the joint design as follows.:For pin joints, only axial force and shear were considered, while for rigid joints, bending moments were considered in addition to axial force and shear. To make the first floor rigid, a concrete floor slab was placed and connected to the sheet pile of the wall, and all nodes of the first floor were connected to each zone. The building will be constructed of SM-J295 hat-shaped steel, which is specified for use in the building basement envelope. Because the steel sheet piles in the exterior walls will have openings for daylighting, the cross-sectional performance of the beam elements used in the analytical model will be based on the two parameters shown in **Table 3**. Since the steel sheet piles are to be exposed to the frame, the cross-sectional performance used in the design should be the cross-sectional performance that takes corrosion into account.

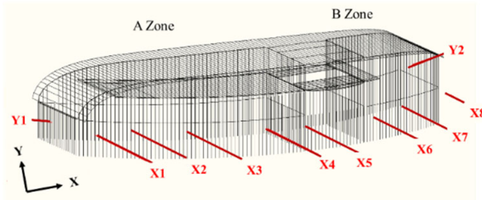


Fig. 6 Structural analysis model

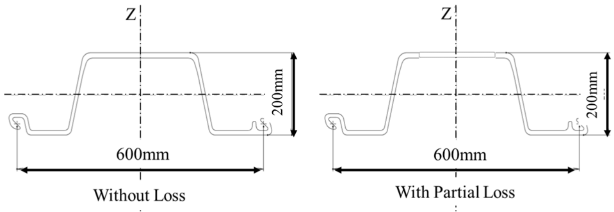


Fig. 7 Cross-sectional shapes of steel sheet piles

Table 3. Cross-Sectional Parameters

		Without Loss		With Partial Loss	
		No Corrosion	Corrosion	No Corrosion	Corrosion
Width	(cm)	60.0	-	60.0	-
Height	(cm)	20.0	-	20.0	-
Area	(cm^2)	111.2	94.5	80.8	68.7
Moment of Inertia (I_Y)	(cm^4)	7,250.0	6,162.5	3,300.3	2,805.3
Moment of Inertia (I_Z)	(cm^4)	39,932.8	33,942.9	38,548.3	32,766.1
Section modulus (Z_Y)	(cm^3)	705.0	599.3	508.5	432.2
Section modulus (Z_Z)	(cm^3)	1,254.1	1,066.0	1,198.6	1,018.8

3.2. Boundary conditions of the structure

Fig. 8 shows the boundary conditions of the structural analysis model used in the design of this building. The joint conditions between sheet piles and connecting beams were set for each street in the perimeter. For the underground portion, the out-of-plane ground reaction coefficient and in-plane ground reaction coefficient were calculated based on the Guidelines for the Construction of Highway Bridges and their Commentary (IV Substructure), and out-of-plane springs and shear springs were set, and the lower end was pin-supported.

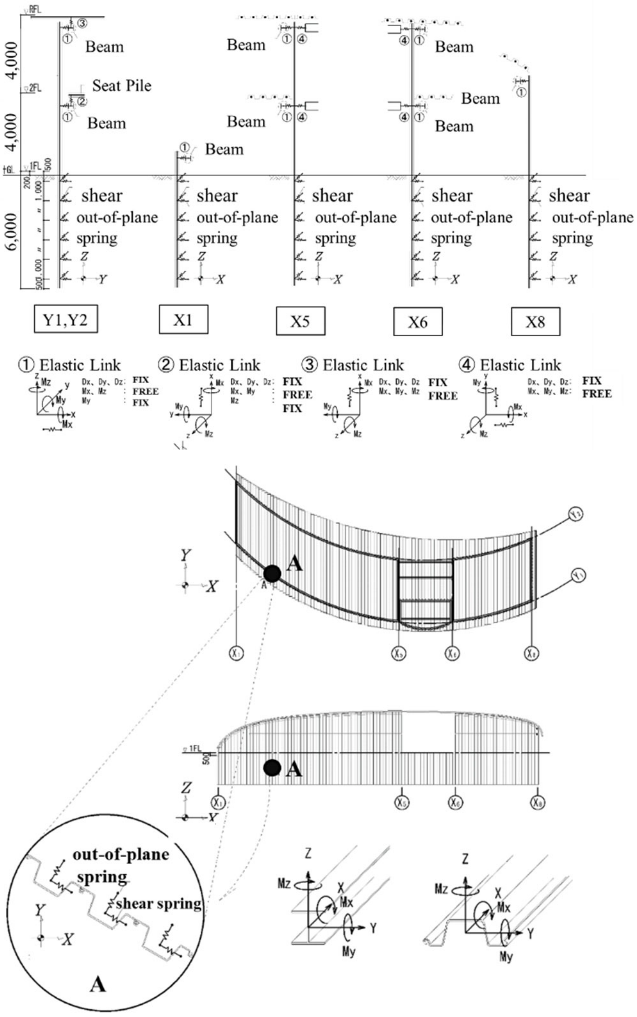


Fig. 8 Boundary conditions

4. Discussion of the study and results

The main structural members of this building are all composed of steel sheet piles, which has inherent challenges that are different from those of ordinary structures. We addressed those challenges and confirmed the safety of the building. Typical issues are as follows.

(1) Since the building requires ministerial certification, it is necessary to confirm the safety of the foundation in the secondary design. Stresses in steel sheet piles (columns) integrated with the foundation must be calculated using the seismic deformation method to confirm that both stress and deformation are safe.

(2) The out-of-plane direction of steel sheet piles is less rigid, resulting in greater deformation. It is necessary to confirm that the steel sheet pile is within the elastic limit capacity at the interlaminar deformation angle generated by a major earthquake, even if the P-δ effect is taken into account.

(3) The 2nd floor and R-story roof are restrained by steel sheet pile intangibility, but there is no concrete slab, so a rigid floor is not established. However, the possibility of restraint by interlocking is considered, so the effect of transitional shear forces from Zone A to Zone B zones should be considered.

(4) In the underground portion, the interlocked sheet piles are further constrained by earth pressure. The effect of the integrated subterranean part should be taken into consideration.

(5) Steel sheet piles on the floor and steel sheet piles on the wall are connected by horizontal joint beams on the floor. The stress in each member of the joint should be within the elastic limit capacity even in the event of a major earthquake, and the structure should be designed to prevent collapse.

(6) The foundation is a pile foundation type that considers the circumferential friction of steel sheet piles. Since the pile is not expected to have a tip bearing capacity, it is necessary to confirm the bearing capacity by loading tests.

4.1 Cross-sectional calculation of main members

The cross-sectional calculation of steel sheet piles was performed using the following equation[3)], considering the bending moment and axial force in two directions.

$$\frac{M_Y}{f_b \cdot Z_Y} + \frac{M_Z}{f_b \cdot Z_Z} + \frac{N}{f_c \cdot A} \leq 1.0$$

The two reinforcement methods are shown in **Fig. 9**.

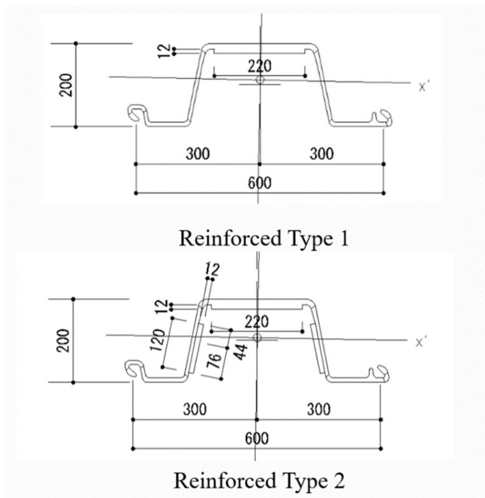


Fig. 9 Reinforcing steel sheet piles

4.2 Joint design

The steel sheet piles in the perimeter walls are connected to the upstairs floor and roof via a connecting beam that runs along the perimeter. The connecting beams and floor steel sheet piles are bolted together at their ends to transmit stress to the columns (wall sheet piles) via connection plates. Stress is also transmitted to the columns by bolted joints between the connecting beams and columns. **Fig.10** shows the locations of the joint beams and the floor and walls. **Fig. 11** shows a detailed cross-sectional view of the joints between the beams and the floor and walls. **Fig. 12** shows a detailed drawing of each type of connection.

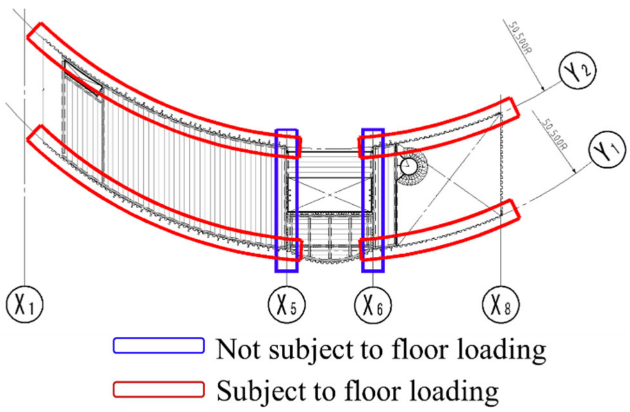


Fig. 10 connecting beams and floor and wall attachments

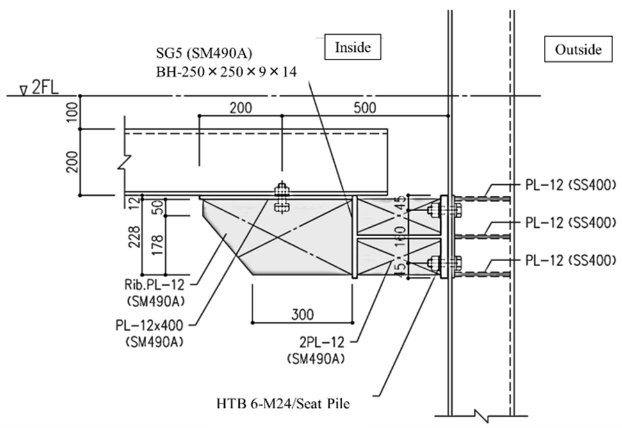


Fig. 11 Detail of connecting beam, floor, and wall

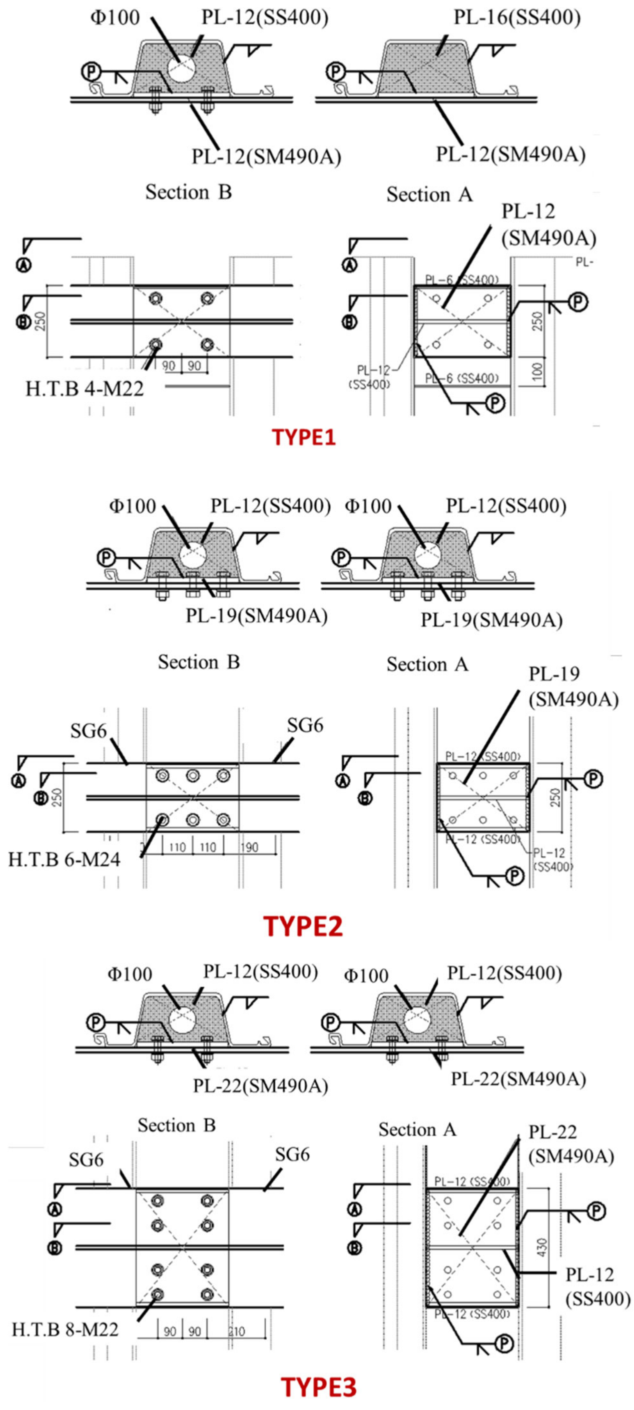


Fig. 12 Details of each joint

(1) Examination of bolt tension joints

Since the steel sheet piles and connecting beams of the floor are pin-jointed, no moment is generated. However, because of the distance between the slab anchorage and the wall, additional bending moments were considered in the calculations by assuming the floor sheet pile ends to be anchored. Therefore, a bending moment is generated at the end of the portion connecting the connecting beam to the column due to the long-term floor load and horizontal force during an earthquake. It was confirmed that the bolts did not fail in shear even when tensile force was generated on the bolts due to the bending moment. The area where the tensile force on the bolt is maximum is the second floor in zone B. This area was designed with connection type 3 (**Fig. 13**). The connecting beam was designed as a built-H section with different widths for the upper (B x t = 430 x 22) and lower (B x t = 250 x 14) flanges to ensure the required number of bolts on the connection surface with the exterior steel sheet pile.

From stress diagram **Fig.14 and Fig.15**,

M_1=16.2+126.6=142.8kNm

M_2=23.7+115.6=139.3kNm

M_D=max(M_1,M_2)=143kNm

Q_D=13.3+21.4=34.7kN

Comparing the tensile force P_{D1} generated in one bolt from the design moment M_D to the bearing capacity of the bolt.

P_{D1} = 143/0.340/4 pcs = 105.0 kN < 174.0 kN (M22) OK

The outer bolts are,

P_{D1}'=105kN×215/170=132.8kN＜174.0kN(M22) OK

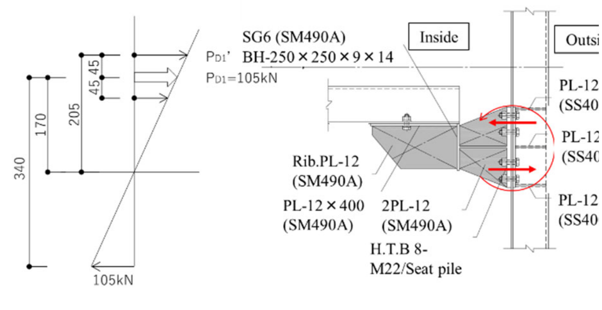


Fig. 13 Connection detail drawing

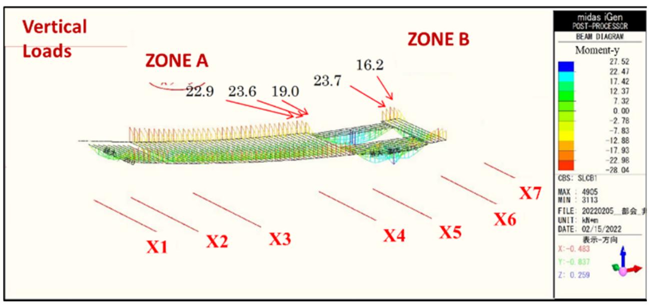


Fig. 14 Long-term bending moment (kNm)

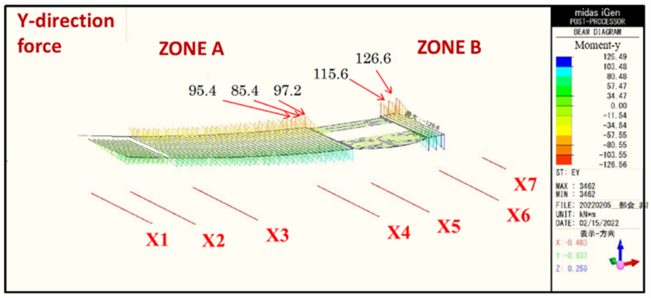


Fig. 15 Bending moment Y direction(kNm)

(2) Type 3 joint plate study

The connecting plate is attached to the web of the steel sheet pile by full penetration welding in the shape of a CT. The plate is attached to the top and bottom to provide four-sided restraint. The thickness of the steel sheet pile is 11mm and the thickness of the connecting plate is 22mm. Because of the difference in thickness, the boundary condition at the outer perimeter was set as a pin with free rotation. It was confirmed that the combined stresses due to shear and pullout forces were within the short-term allowable stress of the steel.

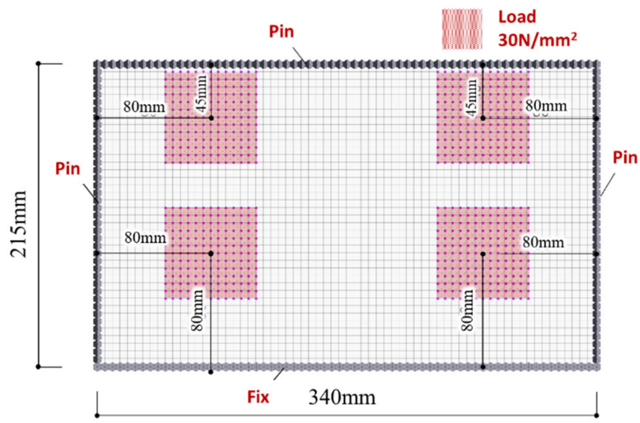


Fig. 16 Analysis model

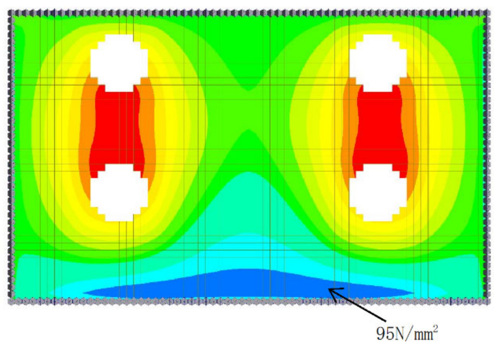


Fig. 17 Stress σ_x(N/mm^2)

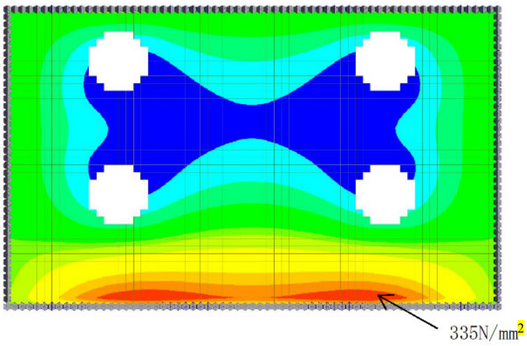


Fig. 18 Stress σ_y(N/mm^2)

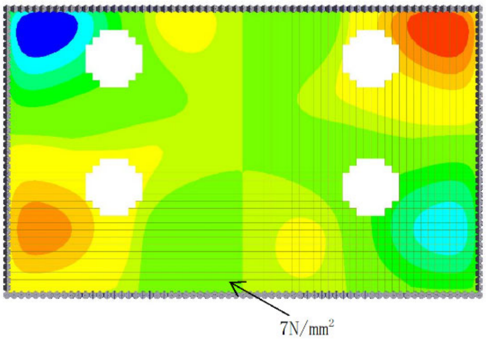
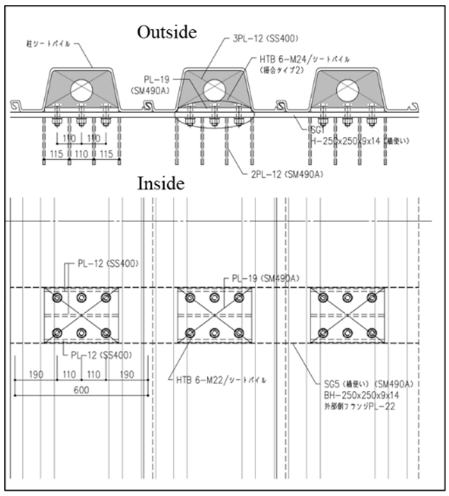


Fig. 19 Shear stress τ_{xy} (N/mm^2)



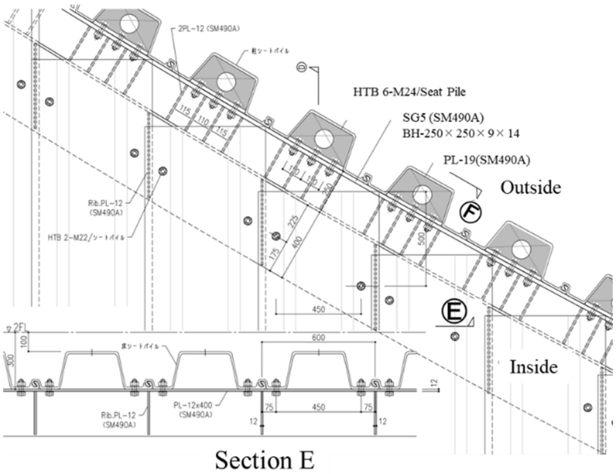
Section F

Fig. 20 Detail of Zone A 2nd floor (between X3-4 on Y2 Street)

Fig. 21 Type 2 **(Fig. 12)** a view looking up at the second floor ceiling

(3) Consideration of H-beams and rib plates for joints

Fig. 22 shows the Analysis model for Type 2.



Section E

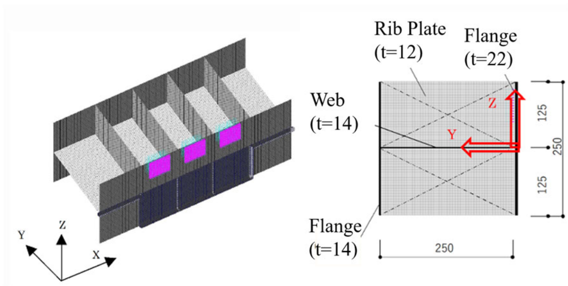


Fig. 22 Type 2**(Fig. 12)** Connected Beam Analysis model

4.3 Bearing capacity of pile foundation

The foundation of this building is of the pile foundation type that considers the circumferential friction of the columns (steel sheet piles) with the steel plates in the ground. Loading tests were conducted to confirm the bearing capacity of the steel sheet piles. [4)]

The loading test location was at the center of the building（**Fig.23**）, and the test pile consisted of three sheet piles that were jointed and press-fitted together.

Ultimate bearing capacity Ru（**Fig.24**）

= 1022 kN/3 pcs = 340 kN

Long-term allowable bearing capacity Ra = 340 kN/3

= 113 kN

Where the bearing reaction force exceeded the allowable bearing capacity, bolted and corner-welded joints were used to transfer the axial force to adjacent sheet piles. The test values of bearing capacity were set to be less than 0.75 in the long term and 0.5 at the end of the life time, taking into account the ground variation and the factor of safety.

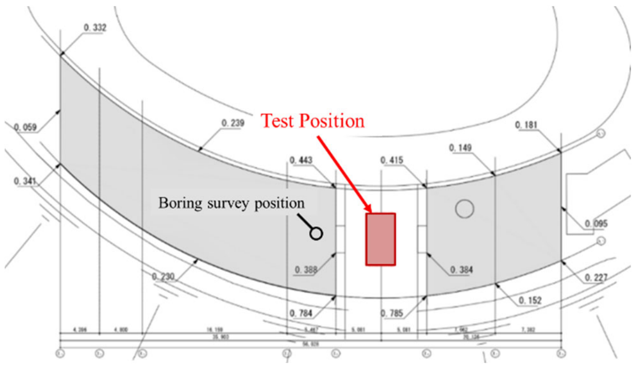


Fig. 23 Location of test pile

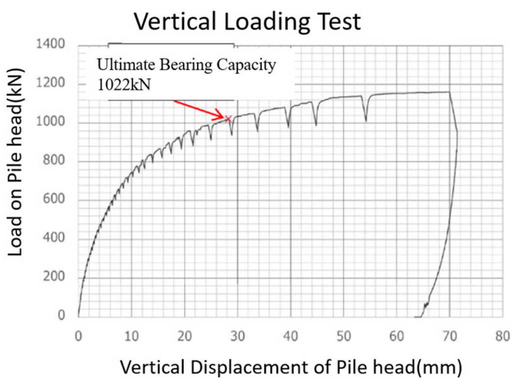


Fig. 24 Vertical loading test result for SM-J295 steel sheet pile

5. Construction planning and results

The building used 532 steel sheet piles for the walls and floors, weighing approximately 500 tons, and the connecting beams for the floor supports weighing approximately 90 tons. Since the perimeter of the building is surrounded by 60-cm wide mated steel sheet piles, the joint beams for the second floor were placed in advance of the construction. H-shaped joint beams were installed on the scaffold trestles to guide the sheet pile press-in (**Fig.25**).

Since the maximum height of the construction machine was 8 m, SILENT PILER with an open chuck front end and a crawler mounted on a trestle was planned so that the machine could press-in the sheet pile after moving backward and forward on the ground (**Fig. 26 and Fig. 27)**. The floor sheet piles were installed in parallel with the wall sheet piles. Since the floor sheet piles also needed to be fitted with joints, the plan was to insert them horizontally before installing the wall sheet piles on one side (**Fig. 28**). The bridge in the center was to be assembled on the ground, dropped from the top, and installed at the second-floor level. After the second-floor sheet piles were installed, the remaining wall sheet piles were pressed in (**Fig. 29**). The press-in machine with crawler was able to perform the installation by modifying the machine height so that it could travel and press-in under the second-floor beam even with sheet piles for the second floor in place (**Fig. 30**). For some wall sheet piles that could not be installed the Crawler Unit with the Reaction Stand, SILENT PILER was installed on the top of the sheet piles and performed piling works at height (**Fig. 31**). All of the wall sheet piles, including the corners, were fitted together to restrain the ground beneath the building. The roof is curved in three dimensions, requiring high fabrication and installation accuracy of the connecting beams and steel sheet piles. The second-story floor sheet piles were placed in advance of the second-story connecting beams to ensure that the R-story beams could be attached to the sheet piles at a predetermined position. The roof sheet piles were installed with the same joints as the second-floor sheet piles to ensure watertightness (**Fig. 32**).

Fig. 25 Second floor connecting beam installation

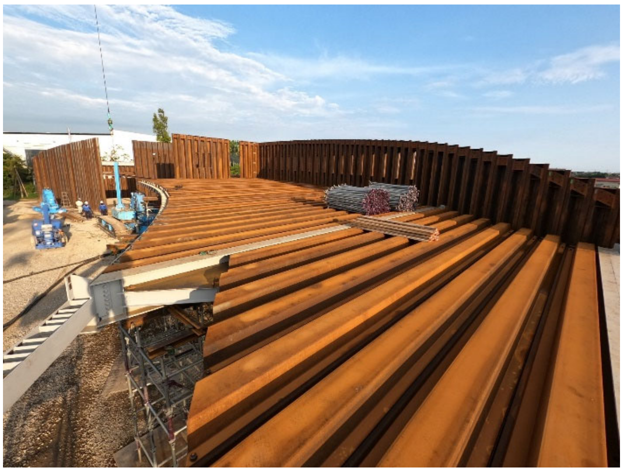


Fig. 28 Second floor sheet pile installation

Fig. 26 The Crawler Unit with the Reaction Stand

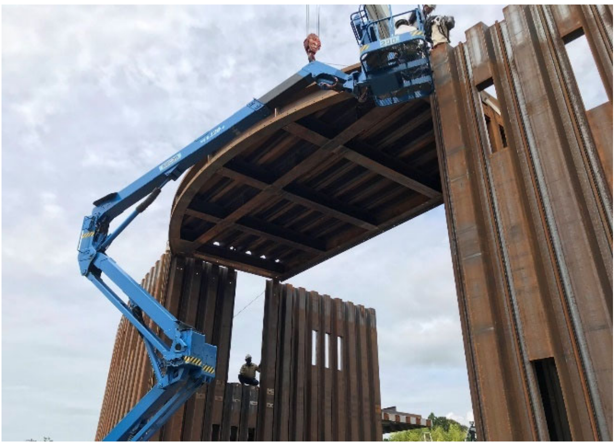


Fig. 29 Installation of central second floor beam and floor sheet piles

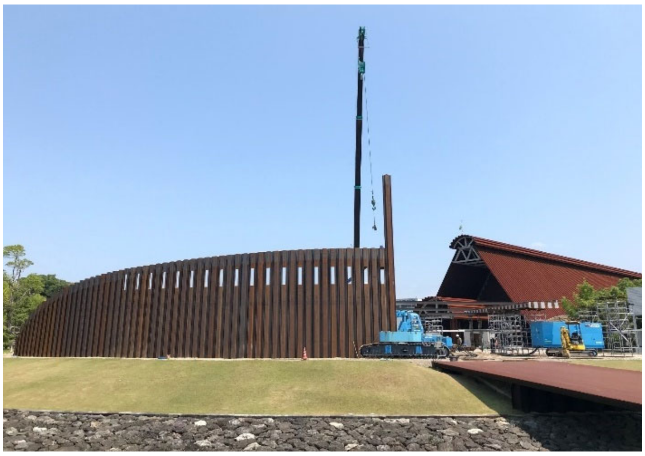


Fig. 27 Press-in steel sheet pile

Fig. 30 The Press-in machine on the Reaction Stand with crawler unit

Fig. 31 Steel sheet pile press-in
(piling work at GL+8m height with SILENT PILER™)

Fig. 32 Roof sheet pile installation

6. Conclusion

The "Research Building" is a facility for research on press-in technology for steel sheet piles and steel pipe piles, with a theater room and exhibition space for visitors to learn about the past, present, and future of press-in principles and press-in technology. The main structural member used was steel sheet pile (SM-J295). While taking advantage of the flexibility of steel, the strength of the horizontal and vertical joints was secured to create a structure that works as a whole from the roof to the side walls, absorbing and resisting energy tenaciously. Steel sheet piles were originally used as retaining walls in temporary construction, but they have now demonstrated the technical feasibility for use as structural materials, roofing, and exterior finishing materials. Additionally, due to the already established benefits of mass production, they also offer economic feasibility. Moreover, during removal, the land can be easily restored to its original state simply by extracting the steel sheet piles, which can then be repurposed for other uses. This results in a sustainable structure that can flexibly adapt to changes in time and society. Steel sheet piles are also used as the main structural members of the "Museum of Piling Machines," which was completed earlier. "RED HILL 1967" an information transmission base for press-in technologies of GIKEN LTD. is a facility where visitors can learn about the history of piling machines, the different principles of construction, and the superiority of press-in technology in a building where the advantages of steel sheet piles are utilized.

Acknowledgment

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We, the authors, would like to express our sincere condolences on his passing.

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