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Design of Hanshin Electric Railway Naruo Station with Plank Sheets

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Abstract: This paper reports a Japanese railway station's design that consists of minimal architectural materials and a structural experiment with plank sheets as an element of shell structure. The station's space is created by unifying walls and ceilings with plank sheets that do not require any support. Stairs, escalators, elevators, and signs are clearly visible as symbolic components for the passengers.

1. Introduction

Graduate students in Mukogawa Women's University's (MWU) Architecture Major participate in on-going projects both on and off of campus and experience involvement in such practical training as the design of new buildings, reconstruction, preservation, and restoration in a class called, "Practice in Architectural Design," under the supervision of a first class authorized architecture design office: Architecture and Urban Design Studio, MWU. At the Hanshin Electric Railway Naruo Station, which is located just minutes from MWU, students have worked on CG perspective drawings, mock-ups, researched costs and construction methods, and proposed such designs as exteriors, platforms, and concourses. In meetings, the students themselves conducted presentations and used their own drawings and mock-ups. The construction of Naruo Station's down-platform was completed in March, 2015, and now the up-platform is under construction. This paper reports a station design that consists of minimal architectural materials and a structural experiment of plank sheets as shell structure elements.

Figure 1. Birds-eye view of Hanshin Electric Railway Naruo Station

Figure 2. View from southeast side

Figure 3. View of east end of platform from southeast side

Figure 4. Meeting with Hanshin Electric Railway

Figure 5. Explanation of construction method using 1/10 scale model

Figure 6. Explanation of appearance design using 1/10 scale model

Figure 7. Explanation of appearance design using 1/30 scale model

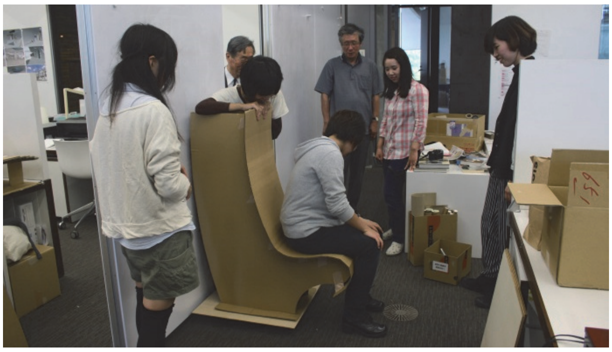


Figure 8. Consideration on the shape of a chair by mock-up

Figure 9. Chair on train platform made of curved steel plates. Lightness was imagined by adopting curved thin steel plates as material, preserving the atmosphere produced by curved surfaces of plank sheets. We investigated the seat surface's height and the required curvature of the back surface comfort by producing full-scale, cardboard mock-ups and actually sitting in them. The seat surface is deep, and the waist part is convex so that the chair's back surface does not press the stomach and make contact with the entire backs of people. A 2.3-mm-thick steel plate was used for the supports, and decorative veneered plywood was used for the seat's surface.

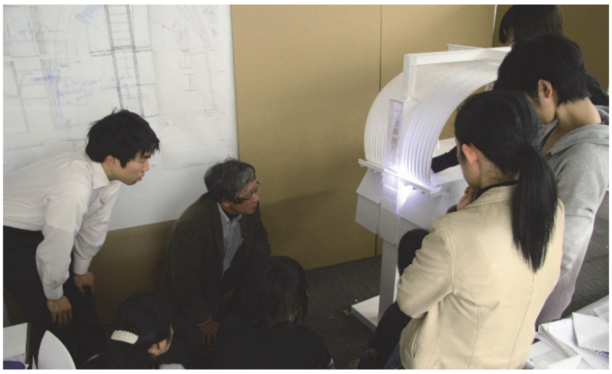


Figure 10. Analyzing lighting plan using 1/10 scale model

Figure 11. Confirmation of scale sensitivity using full-scale drawings

Figure 12. Scrutinizing luminaire and cable rack mock-ups

Figure 13. Scrutinizing a mock-up sign

2. Design Concept of Station with Plank Sheets

2.1. DESIGN FASHIONING IMAGES OF HISTORICAL AND TRADITIONAL LANDSCAPES

In ancient times, the Naruo area was considered a scenic spot by Waka poets, a sentiment that has vanished. Wind through rows of pines on the seashore and sailing boats coming and going can be imagined. The curves of plank sheets that cover the station platforms are inspired by sails filled with wind.

Figure 14. View from south west side

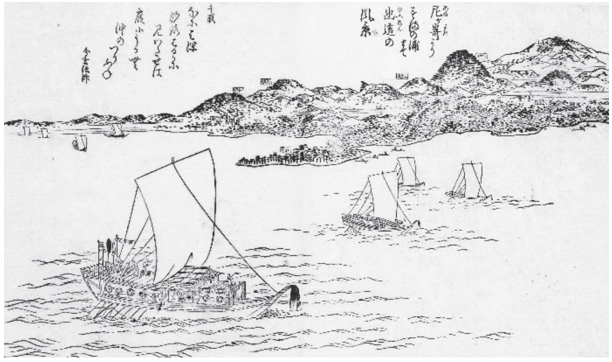


Figure 15. Sightseeing scene from Amagasaki to Sumaura in “Settsu-meisho-zue” from Mukogawa Women's University Library

2.2. SYMBOLIC SPACE

Symbolic characteristics, which is generally required for station spaces, denotes the relationship between objects and people, such as the color of traffic lights; people act unconsciously when they see red, for example. Symbolic space has characteristics that cause people to act unconsciously. Owing to symbolic spaces in stations, when a person sees a staircase after getting off a train, she unconsciously walks toward it, or when she sees an entrance gate, she walks toward it to find the exit. At train stations, stairs, entrance gates, escalators, elevators, and signs function as symbolic components for passengers as well as the colors of traffic lights. Such symbolic components must be clearly visible without being interrupted by other components of the space. Such other components as structures, facility equipment, and advertisements (except symbolic components) should be inconspicuous. However, since these non-symbolic components are not regulated at all in stations in Japan, they are scattered everywhere, complicating comprehension of the perception of space. Naruo Station was designed with plank sheets to create a symbolic space.

Figure 16. View east of platform

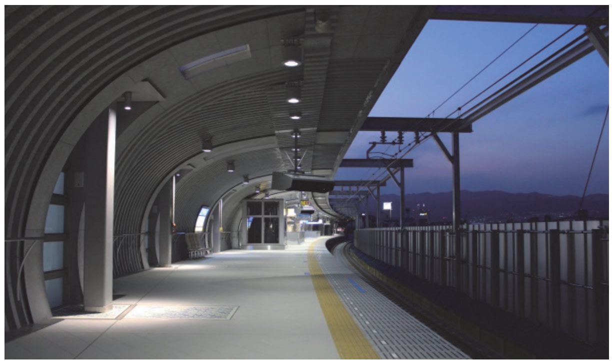


Figure 17. View west of platform at night

2.3. SIMPLE AND HOMOGENEOUS SPACE CREATED BY PLANK SHEETS

Plank sheets are mainly used for the civil engineering structures of bridges, pedestrian decks, retaining walls, and so forth. We used plank sheets with a 2.7-mm thick, 100-mm high steel plate that is curved gently and fixed them at two points: the roof of the railway track side and the floor of the track's opposite side. Plank sheets do not require any support or finishing materials. Each platform is composed of the curves of the uninterrupted sheet that consist of the roof and the walls. Such plank sheets provide the meaning of symbolic space by highlighting such necessary compartments in stations as stairs and their role as a dynamic station component in harmony with high-speed trains that represent advanced technologies. Plank sheets also have sufficient strength that signs can be hung on them.

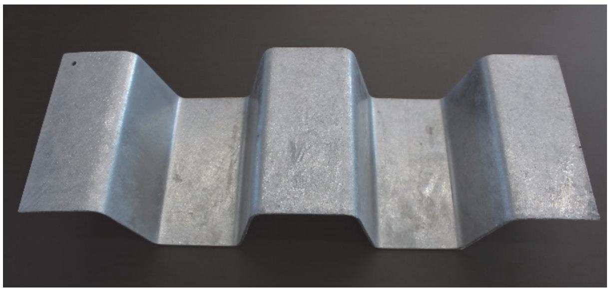


Figure 18. Plank sheet with a 2.7-mm thick, 100-mm high and 570-mm wide steel plate

2.4. MEASUREMENT OF SURFACE TEMPERATURE OF PLANK SHEETS

A plank sheet is a corrugated steel plate that we used as a constructional material that covered the platform without requiring any finishing. Because its steel surfaces are exposed, they can be easily touched by the station users. To determine the temperature incensement of plank sheets exposed to the summer heat, an experimental measurement was carried out using a mock-up at Kami Koshien campus of Mukogawa Women's University in August 2012. The mock-up faced south to simulate the down platform on the south side that receives large heat loads from solar radiation. We measured the surface temperatures of several points (500, 1000, 1500, and 2000 mm above the ground) in each direction. In addition, we conducted a water sprinkling experiment in August to determine how to decrease the surface temperature.

Figure 19. Plank sheet mock-up

Figure 20. Measurement of plank sheet's surface temperature

The maximum temperature during the measurement period was 49ºC. The daily maximum temperature was around 45ºC, which was measured between 10:30 AM and 14:00. The east surface's temperature was highest in the morning, and the temperatures of the south, west, and north surfaces followed in descending order. While the temperature of the west surface was highest in the evening, the south, east, and north temperatures followed in descending order. In the water sprinkling experiment, we sprinkled 24-29ºC tap water from the top of the mock-up of the plank sheet. In each case, the surface temperature of the north surface (the platform side) became constant five minutes after the sprinkling started and dropped to about 30ºC. This result suggests that a small amount of tap-water sprinkling can effectively decrease the surface temperature.

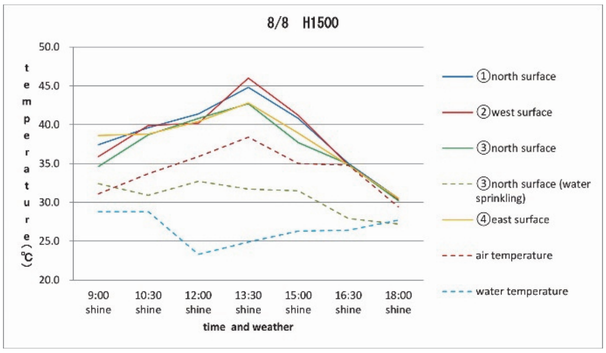


Figure 21. Measurement results of surface temperature of plank sheets

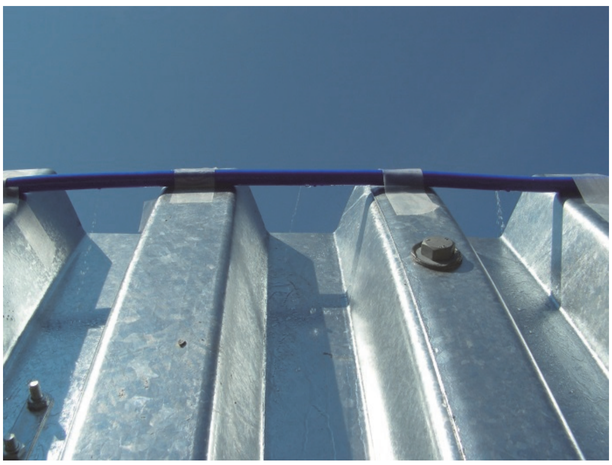


Figure 22. Water sprinkling experiment of plank sheets. We sprinkled 24-29ºC tap water from the blue hose.

2.5. CONSTRUCTION OF PLANK SHEETS

Hot-dip galvanizing, phosphate-treated plank sheets were used as a construction material that covered the platform. 7500-mm long, 570-mm wide plank sheets were attached to the roof on the rail side and to the floor on the platform side. Curved plank sheets were connected with high-strength bolts at 500-mm intervals in both vertical and horizontal directions and function as a structural element to transmit the in-plane shear force.

Figure 23. Plank sheet mock-ups

Figure 24. Plank sheets temporarily placed at construction site

Figure 25. Steel frame before setting up plank sheets

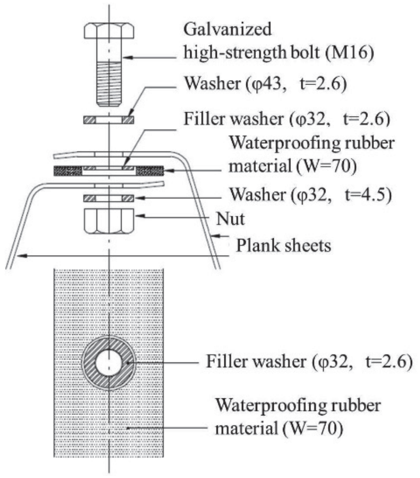
Figure 26. Set-up of plank sheets

Figure 27. View east of platform

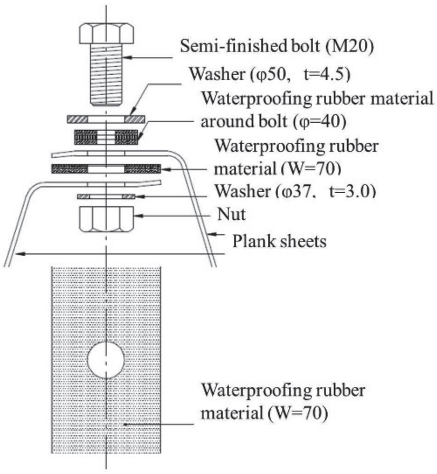
Figure 28. View west of platform

3. Structural Experiment with Plank Sheets

This project also conducted a structural experiment on the connection between plank sheets applied to the design of Naruo Station. Generally, plank sheets are connected with semi-finished bolts (Fig. 29(a)) at intervals of around 500-mm, and the shear transfer between plank sheets through the bolts is not considered in the design. In this project, we proposed and examined the connection details with high-strength bolts (Fig. 29(b)) by relying on the frictional resistance between plank sheets. The shear performance and capacity of the connections between the plank sheets using high-strength bolts were investigated and confirmed through structural experiments.



(a) Connection with high-strength bolt



(b) Connection with semi-finished bolt
Figure 29. Connection details

3.1. EXPERIMENT SET-UP

We conducted a structural experiment on the connection between plank sheets using a large-scale experimental apparatus installed at the Structural Laboratory in MWU's Architectural Department (Fig. 30). This apparatus enables pseudo-static cyclic loading in one horizontal direction and one vertical direction to simulate earthquake loading. The specimen arrangements in the experimental apparatus and its loading mechanism are shown in Fig. 31. Each specimen consists of plank sheet A (width: 1,640 mm, height: 570 mm) and plank sheet B (width: 2,000 mm, height: 570 mm). These sheets were connected with three bolts (Fig. 32). The specimen details consisting of plank sheets A and B are shown in Fig. 33. To minimize their flexural deformation, several channel members were transversely welded to them. We investigated three specimens with a connection using high-strength or semi-finished bolts (Table 1). The connection details are shown in Fig. 29. Specimens 1 and 2 had connections using the high-strength 3-M16 bolts that we proposed in this project and examined. Specimen 3 had connections using semi-finished 3-M20 bolts, which are typically used. Both types of connections were waterproofed with rubber material.

Figure 30. Large-scale structural experiment apparatus

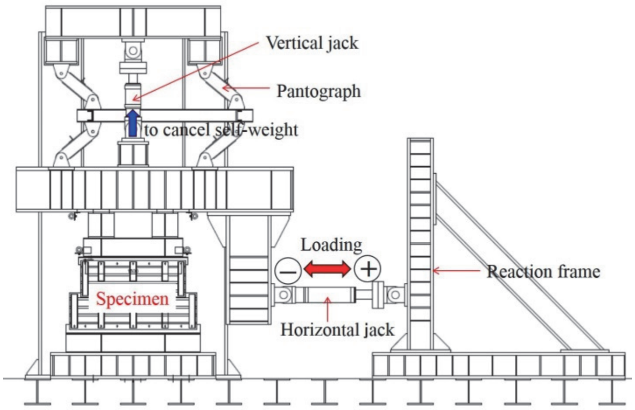


Figure 31. Test set-up

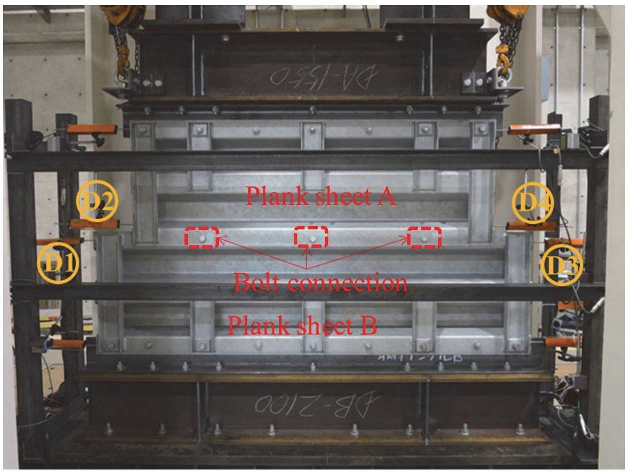
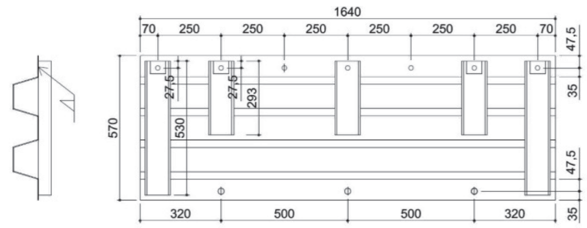
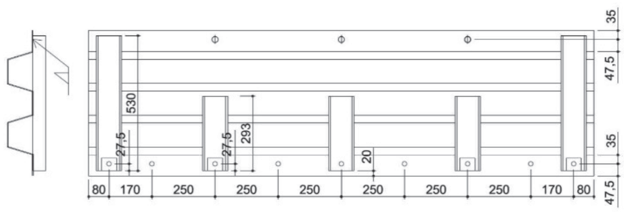


Figure 32. Plank sheet specimen

A horizontal jack provided the specimen with cyclic shear loading, and a vertical jack provided it with upward force to cancel the self-weight of the specimen and the experimental apparatus to subject the connection to pure shear loading (Fig. 30). The loading history of each specimen is provided in Table 2. Since it was intended to evaluate the shear performance and the capacity of the connection between plank sheets under many loading reversals during earthquake excitations, we selected cyclic loading in both positive and negative directions. Specimen 2, which has the same connection details as Specimen 1, was loaded up to a relatively small displacement cycle of ±5 mm to observe the damage around the bolt connection under service loading after the experiment and disassembling the specimen. We measured the shear deformation at the connection by four displacement transducers, D1, D2, D3, and D4 (Fig. 32), and defined the shear deformation at the connection as an average value of the relative displacement of D2 to D1 and the relative displacement of D4 to D3.



(a) Plank sheet A



(b) Plank sheet B

Figure 33. Details of plank sheet specimen

Table 1. Specimens with connection details

Specimen	Connection	Hole diameter
1	M16, High-strength bolt (proposed)	18 mm
2		
3	M20, Semi-finished bolt	24 mm

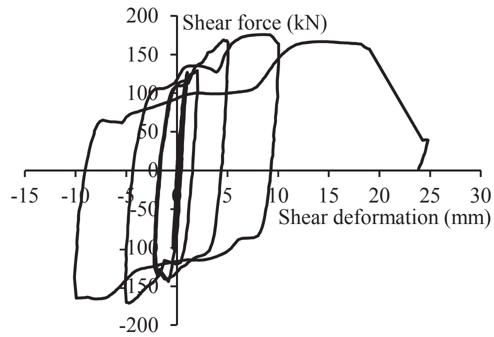
Table 2. Loading history

Specimen	Target load or displacement
1	±51 kN→±102 kN→±1 mm→±2 mm→±5 mm →±10 mm→±20 mm
2	±51 kN→±102 kN→±1 mm→±2 mm→±5 mm
3	±2 mm→±5 mm→±10 mm→±20 mm→±30 mm

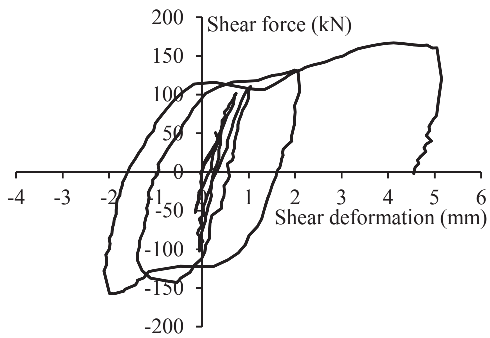
3.2. TEST RESULTS

Figure 34 shows the relations of the shear force and the shear deformation at the connections between the plank sheets for all the specimens. The shear force was measured by load cells installed at the horizontal jacks. Fig. 35 shows the relations of the shear force and the shear deformation around the stage of the occurrence of the slip behavior for Specimens 1 and 2. Here, the stage is shown when slip behavior was observed. The damage observed around the bolt connection at the end of the loading for each specimen is shown in Fig. 36. Specimens 1 and 2 with a high-strength bolt connection exhibited large hysteretic loops, resulting in large energy absorption (Figs. 34(a) and (b)). This was due to the frictional resistance between the plank sheets provided by the high-strength bolts. The failure pattern of Specimen 1 was caused by the rupture of the plank sheets in the out-of-plane direction around the bolt (Fig. 36(a)). Also, in Specimen 2, there was very slight damage after ±5 mm displacement (Fig. 36(b)). In contrast, Specimen 3 with a semi-finished bolt connection exhibited slip-pinching behavior, which is typical of bearing connections (Fig. 34(c)). This was caused by no frictional resistance between the plank sheets provided by the semi-finished bolts, and shear force is transmitted between the plank sheets and bolts by the bearing force. Therefore, when the bolt was not in touch with the edge of the bolt hole, there was almost no resistance and only the displacement increased. The failure pattern of Specimen 3 bore the failure of the plank sheets, and elongation of the bolt holes due to bearing force was observed (Fig. 36(c)).

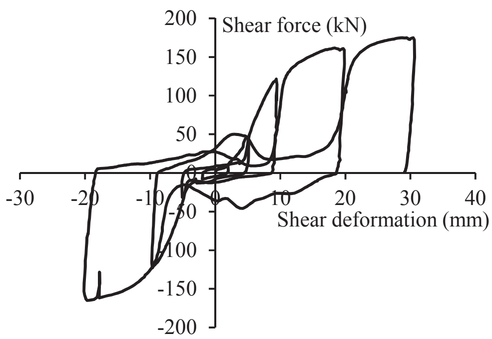
Table 3 summarizes the capacity of the high-strength bolt connections to the slip obtained in our experiment. Here, the capacity to the slip per bolt was calculated as the force at the occurrence of the slip behavior in Fig. 35 divided by the three connecting bolts, which were 47.9 kN and 47.7 kN for Specimens 1 and 2. Since the allowable slip strength for the design is 34.0 kN for high-strength M16 bolts, the safety margins for Specimens 1 and 2 are 1.41 and 1.40. Therefore, the connection between the plank sheets using high-strength bolts possessed sufficient slip capacity. Also, the connection with the high-strength bolts possessed much larger hysteretic energy absorption than the one with semi-finished bolts (Fig. 34).



(a) Specimen 1 (high-strength 3-M16 bolts)

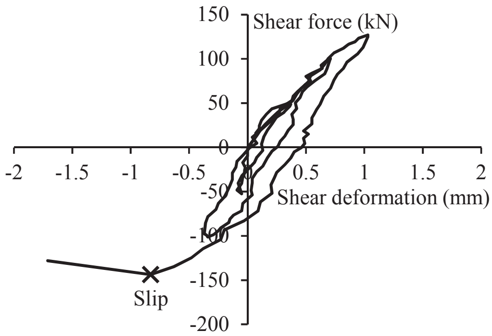


(b) Specimen 2 (high-strength 3-M16 bolts)

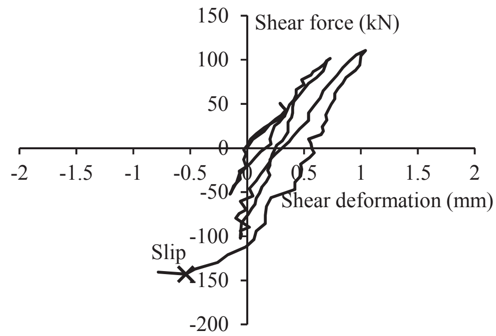


(c) Specimen 3 (semi-finished 3-M20 bolts)

Figure 34. Relations of shear force and shear deformation

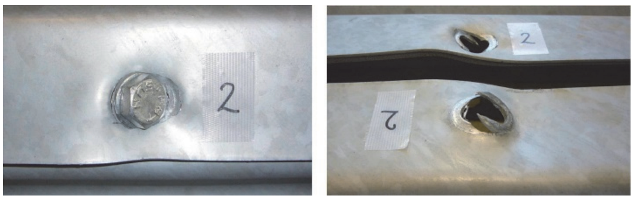


(a) Specimen 1 (high-strength 3-M16 bolts)

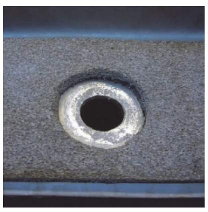


(b) Specimen 2 (high-strength 3-M16 bolts)

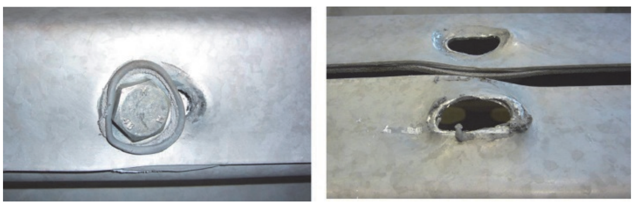
Figure 35. Relations of shear force and shear deformation



(a) Specimen 1 (high-strength 3-M16 bolts)



(b) Specimen 2 (high-strength 3-M16 bolts)



(c) Specimen 3 (semi-finished 3-M20 bolts)

Figure 36. Damage around connection observed at end of experiment

Table 3. Capacity of bolt connection to slip

Specimen	Displacement at slip (mm)	Force at slip (kN)	Capacity to slip per bolt (kN)	Safety margin
1	-0.83	-143.8	47.9	1.41
2	-0.54	-143.0	47.7	1.40

3.3. CONCLUDING REMARKS

We proposed high-strength bolt connections by relying on frictional connections, even under a condition where we inserted waterproofing rubber material, to transmit shear force between plank sheets. We confirmed that high-strength bolt connections between plank sheets outperformed the semi-finished bolt connections in terms of stiffness and hysteretic energy absorption. Based on experimental data, sufficient fundamental knowledge was obtained to design plank sheets as structural elements to transmit in-plane shear force.

4. Summary

This paper reported a design of the Hanshin Electric Railway Naruo Station and a structural experiment of plank sheets as an element of shell structure. A platform with plank sheets does not require any support, and stairs, escalators, elevators, and signs are clearly visible as symbolic components for passengers. This project showed the effectiveness of plank sheets, which aren't generally used as architectural materials, especially in finishing or structural materials. Our method, which used plank sheets as a structural element and composed architectural space with minimal materials that unified the walls and ceilings in Naruo station, will be effective in designing such architectures as stations where symbolic characteristics are required.

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