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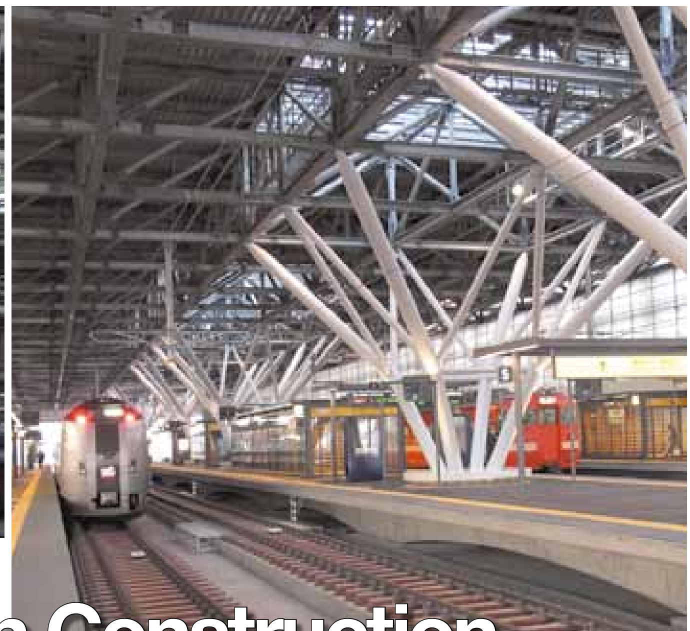

Special Issue

Advanced Large-span Construction

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Steel: The Leading Player for Enhanced Large-span Hybrid Structures

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Mamoru Kawaguchi: Former President of Int. Assoc. for Shell & Spatial Structures; Graduation from Fukui University in 1955 and Dr.Eng. Degree from Tokyo University in 1966; Involved in structural designs of Tokyo Olympic Swimming Hall, Singapore Insoor Stadium, Barcelona Olympic Sports Palace, etc.; IABSE International Award in 1995 and IASS Torroja Medal in 2001

Steel is very often utilized as the leading element of many composite or hybrid structures. It plays an important role as the tensile member to constitute a rational structure of intended specific nature in collaboration with other constituent materials which take parts of compressive, shearing or bending members. It may be interesting to note that the latter members can be composed by materials of various kinds, according to the purposes of design. This article describes some of the author's recent design works in which a variety of materials such as concrete, natural stone, timber, aluminum, and even air have been adopted to constitute rational and esthetic large-span structures together with steel as the leading tensile material.

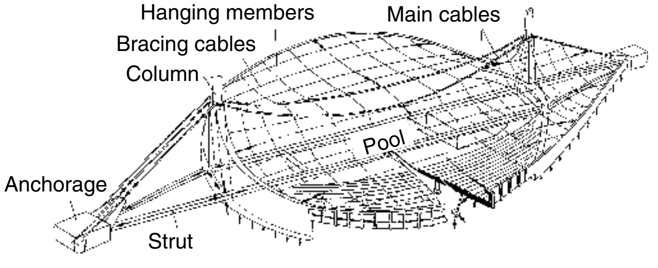
Cable- Steel Hybrid Structure: Semi-rigid Tension Structure (Yoyogi Stadium)

Yoyogi Stadium consists of two major facilities– the first and second gymnasiums. The roofs of both gymnasiums were designed on the principle of tension structures. (See Photo 1)

The first gymnasium originally designed for swimming and ice-skating has a seating capacity of 15,000. In this building, a similar structural system to suspension bridges was adopted for its central structure. Two main cables span 126 m between the two principal columns and 65 m outside them in the backstay. A series of hanging members composed of steel sections span the area between the main cables and the curved RC boundaries surrounding the seats. Penetrating these steel members, a group of bracing cables run along the geodesic lines of the roof surface, which are tensioned to increase the rigidity of the whole roof structure. Initially ropes were proposed to constitute the cable network to form the roof surface, but it was foreseen in the design stage that the roof surface defined by the boundary structures of different characters would not be realized by pure cable nets without largely losing economy. To solve this problem we developed a "semi-rigid" hanging system for the roof which was constituted by tensile members with some bending rigidity and bracing cables. (Refer to Fig. 1)

Photo 1 First gymnasium of Yoyogi Stadium

Fig. 1 Structural System of Yoyogi Stadium



Steel-RC Articulated Hybrid Structure (Tochigi Green Stadium)

Tochigi Green Stadium (Photo 2) was built in 1993 in Utsunomiya City for soccer games. In structural design of this structure, the following attempts have been pursued: 1) Articulation of the structural components, and 2) Prefabricated RC grandstand structures.

The former has been considered important to realize the atmosphere of "floating roofs in a copse" which has been the visual

Photo 2 Floating roof of Tochigi Green Stadium

desire of the architect about the grandstand roofs. For this purpose the supporting structures of the roofs have been articulated into pure tensile and compressive members which have been connected to each other by means of hinges. The articulation makes the cross sections of the structural components smaller, and they are made less expressive of themselves, to achieve the feeling of "floating roofs." The tensile members are designed with steel rods of 32~ 52 mm in diameters, and the compressive members with prestressed concrete piles. This may be the first example in which concrete piles have been used for architectural components without any further finishing. Concrete piles are mass-produced industrial goods of high standard both in dimensional accuracy and material quality. Moreover, surface of concrete piles, prestressed or non- prestressed, is so dense, fine and smooth that we can use them as architectural members without further treatment.

Thus the grandstand and its roofs are constituted by 25 columns of prestressed piles and prefabricated concrete girders which carry the floor panels on them. In the longitudinal direction, the structure is stabilized by means of steel rod bracings, the adjacent columns standing "hand in hand" with each other.

Steel-Natural Stone Hybrid Bridge (Inachus Bridge)

The Inachus Bridge (Photo 3) was constructed in 1994 in the City of Beppu, Kyushu, as a footbridge leading to a scenic park named Minami-Tateishi Koen. The span to be bridged was 34 m. In the process of discussions with the mayor and the staff of the construction division of the city, the author noticed that Beppu had a sister city in China named Yantai which exported granite stone of excellent quality. Laboratory tests proved that the stone was superbly strong and stiff for structural use, and the author decided to adopt the Yantai granite for the structural component of the bridge. The bridge was designed to have a lenticular shape with an arched granite upper chord and a suspended lower chord. In the present design, the granite upper chord plays a dual role of a principal structural member and a deck floor on which people directly step when they cross the bridge.


Photo 4 Onishi Hall

Thus the upper chord consists of 78 blocks of granite 40 cm wide and 25 cm deep with a varying length from 2.6 m to 3.6 m. The whole upper chord is prestressed to produce a literally "monolithic" structural member. The lower chord consists of steel plates arranged into a chain. The upper and lower chords are connected to each other by means of web members consisting of steel tubes arranged to form inverted pyramids in a manner which the author calls an "open-web truss," in which the web of a girder is not "closed" by a repetition of lattice members as in a normal truss. Taking into account the savings in lattice members and connecting details and esthetic advantage of a simpler appearance, the author believes that the open-web truss has a good raison d'être in structural design. The bridge was named "INACHUS (the name of the God for River in the Greek myth) after its completion through a naming competition among the citizens of Beppu.

Steel-Timber Composite Structures

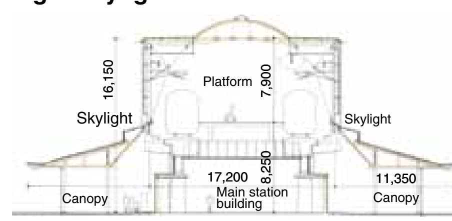
● Steel-Reinforced Timber Structures

Timber is an excellent natural material which can be recycled in the forest. It is also a material that can be felt friendly when exposed to the space of human activity. On the other hand, timber has such drawbacks that it has often very limited strength and rigidity as a structural member. This situation leads to the idea of reinforcing timber members with much stronger materials like steel. A few bridges have already been built on the basis of this idea. The author was recently involved in design of an assembly hall for Onishi Town in which the architect wanted to have a roof supported by a very thin series of timber beams, and he applied steel reinforcement to these timber beams to achieve this requirement in a reasonable way (Photo 4).


Photo 3 Granite Inachus Bridge


Photo 5 Aira Gymnasium

Fig. 2 Hyuga-shi Station



● Steel-Timber Hybrid Structures

Timber as material is equally strong in tension as in compression, but it is much less efficient to join them in tension than in compression. Therefore, a hybrid design in which timber is located to take compression may lead to a good result.

Aira Gymnasium (Photo 5) has a plan of 100 m × 50 m, and its arena is covered by a hybrid timber shell which consists of a laminated curved surface of 200 mm in thickness and steel lattice systems. The timber shell acts typically as a compression member, and serves not only as a structural element, but as sound and heat insulation and ceiling of friendly texture.

Hyuga-shi Station (Fig. 2) has a steel-timber hybrid roof structure in a more complex form to cover a plan of 18 m × 110 m of its rails and platform. Laminated timber beams are fabricated in a shape which ef-

Photo 6 Kochi Station

Photo 7 Prestressed aluminum bridge

Photo 8 Steel membrane air dome

ficiently resists the bending moment due to the horizontal wind loads in collaboration with steel tube members.

The vaulted main roof of Kochi Station (Photo 6) which covers a plan of 39 m × 60 m is constituted by a group of steel-timber hybrid arches in an asymmetric shape having steel knees toward the end of the arches. The hybrid arches rest on the RC supports along the north side of the building, while they are supported by the elevated railway structures on the south side.

Prestressed Aluminum Bridge

A small indoor footbridge connecting a restaurant and an elevator hall was designed in a building in Ginza (Photo 7). It is an aluminum bridge, 6 m long and 1.7 m wide. Aluminum was chosen for its favorable visual texture, no rust, and maintenance-free nature. The whole bridge was cast in the foundry as one block. Since nobody was confident about the reliability of cast aluminum alloy in terms of ductility in tension, a prestress of 300 kN was introduced by means of two prestressing rods, arranged inside the box section of the bridge to avoid tensile stresses in the bridge.

Steel Membrane-Air Hybrid Structures

In the preceding discussion, steel has been exclusively used for tension members, whereas for compressive members such varying materials as concrete, stone, timber, and aluminum have been utilized. One of the most interesting materials that can take only compression may be air. Air cannot resist big tension or shear, but it shows great resistance against volume change. In normal sense, air does not "collapse" or "fracture" in compression. Thus there comes an idea that hybrid structures may be possible using steel for tension and air for compression. The first example realized on the basis of this idea was the stainless steel membrane air-supported roof for the sports complex at Dalhousie University of Halifax, Canada, completed in 1979. This roof covers an area of some 92 m × 73 m of the sports hall. The roof is very flat, and the membrane consists of welded stainless steel sheet 1.6 mm thick.

The author developed an air-supported steel membrane system that could be applied not only to flat but also deep domical profiles. This system which may be referred to as strip (or band or ribbon) system utilizes the strength of metal strips mainly in their longitudinal directions. The strips are longitudinally continuous, and are connected firmly at their ends to the boundaries so as to fully develop their strength in the longitudinal direction, but the adjacent strips are not connected or only secondarily connected to each other along their longitudinal sides. (Refer to Photo 8)

The theoretical existence of a domical surface that develops no hoop stresses under internal air pressure has been known as a configuration corresponding to an extreme condition of rotational membrane shells subject to internal uniform loads. The author named that surface "the shallowest possible pneumatic form," and applied it to steel membrane air domes.

A test dome having a plan of 20 m in diameter was constructed on the above principle using a stainless steel skin of 0.3 mm in thickness. The shape survey of the dome proved that it was sufficiently close to the theoretical one. The dome has experienced a few strong winds including one which blew at a speed of 30 m/sec without any problem.

Conclusive Remarks

Steel is a superb material. It is strong both in tension and compression, showing great rigidity too. It develops its utmost strength especially when it is utilized in tension, whereas its compressive strength largely depends on the way it is applied, causing often much reduction due to buckling. Therefore when we think of developing a new structural component or structural system by combining more than two materials, one of them for tensile strength is almost always steel. But there are many kinds of materials that take the part of resisting compression and/or shear. In the present article, the author tried to show the variety of materials that can be used for those tasks in combination with steel that always plays the role of tensile members. The materials shown in the present article have been concrete, natural stone, timber, aluminum, and even air. There are of course many more materials with which steel can produce new structural components and structural systems.

SkyPark

— A Huge Rooftop, Steel Structure Spanning Three High-rise Towers —

By Yasuhisa Miwa
Project Manager, Steel Structure Engineering Dept., JFE Engineering Corporation

Outline of SkyPark

As its name implies, SkyPark is an aerial park constructed atop three high-rise towers in Singapore (Photo 1). It measures 340 m in total length and 40 m in width. As a new landmark, SkyPark celebrated its grand opening in June 2010 and now stands out among the various facilities operated by Marine Bay Sands Pte Ltd., an integrated resort company in Singapore.

A joint venture between JFE Engineering Corporation of Japan and Yongnam Engineering & Construction Pte Ltd. of Singapore was awarded the contract in April 2008 to construct the steelwork for SkyPark. The joint venture immediately commenced a detailed design and erection plan and in July 2009 started the on-site work to complete the erection of an 8,000-ton steel structure in a mere nine months.

Photo 1 Full view of SkyPark

Structure of SkyPark

SkyPark is composed of two steel truss bridges connecting the three hotel towers (Towers 1, 2 and 3), a steel box girder bridge with a cantilevered structure on Tower 3, and two steel-frame structures atop Towers 1 and 2 (Photo 2) to make an integrated structure. It is designed as an enclosed structure to support the cladding with purlins.

For the bridges connecting the three towers, steel truss bridges were adopted as an alternative to the original design that three main girders are connected by the cross framing transversal beams. Conforming to the curved alignment of SkyPark and the configuration of the towers that support the bridge structures, the trusses have a non-parallel configuration and with changing truss heights as imposed by the aesthetic restriction, thereby presenting the complicated structure seen in Fig. 1.

The structure on Tower 3 is composed

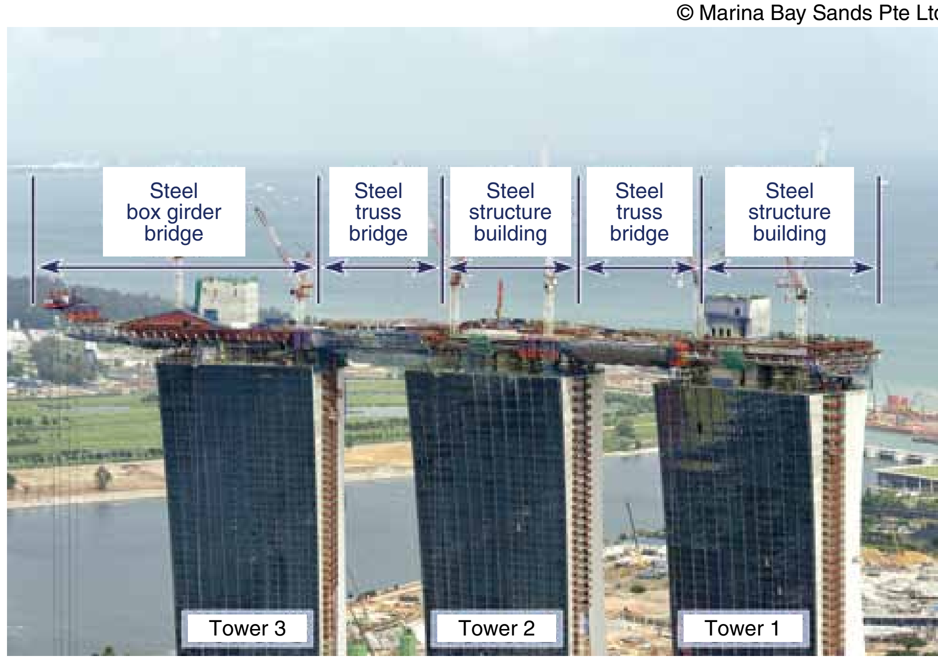


Photo 2 Overall structures of SkyPark

Fig. 1 Section of Steel Truss Bridge

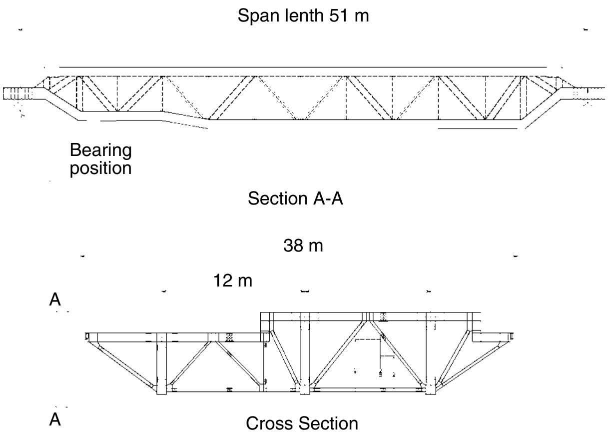
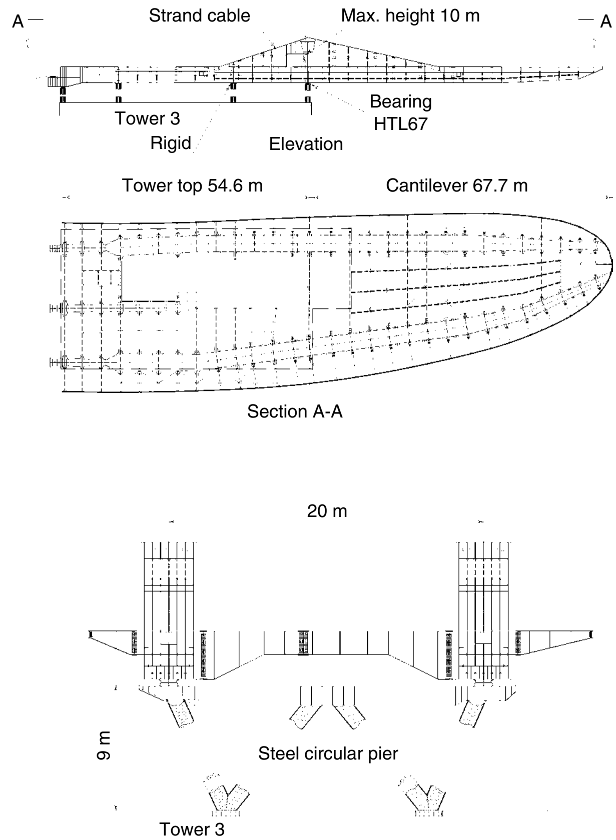


Fig. 2 Steel Box Girder Bridge



of three main girders, with the two on the sides changing from I-section plate girders to box girders in their configuration and extending to form a 67.7 m-long cantilevered structure. The main girders are supported by W-shaped circular hollow columns installed on the RC diaphragm wall of the 55th story, the topmost floor of Tower 3. The main girder on the W Column at grid HTL60 and HTL67 is supported by fixed bearings, and the other points are rigidly connected by weld joining. In order to support the cantilevered structure, a PC strand is placed at the upper flange inside the box girder to be tensioned upon completion of installation of box girders. (Fig. 2). Other special structural approaches are also adopted, such as installation of a tuned mass damper weighing 5 tons at the top end of the cantilevered structure.

Design of SkyPark

While SkyPark is an architectural structure, it has the performance characteristics of a bridge. Accordingly, the design was made in conformity with two standards—BS5950: 2000 Structural Use of Steelworks in Buildings (a British Standard for the design, fabrication and erection of structural steelwork) and BS5400: 1988 Steel, Concrete and Composite Bridges (a British Standard for design and construction of steel, concrete and composite bridges). For the structural materials, S355J of BS EN 10025 Hot Rolled Products of Structural Steels was applied. As for the design of segment joints, the friction grip design was made conforming to the code “Non-slip in service” of BS 5950. Specifically, the code allows friction surface slippage at the time of ultimate loading and resists the ultimate load by means of the shear resistance of the bolts and the bearing capacity of the steel plates. Torque shear-type bolts (S10T) were adopted.

In the design of the bearings, Maurer Sohne GmbH & Co. of Germany was appointed to promote cooperative design. BS5400 Part 3, 1983 was adopted as the design standard.

Because 1.5-hour fireproof performance was required for the area within 10 m of the top of the tower and for the tower exterior, expansive intumescent paint was applied to the section in which the structures are exposed, and sprayed vermiculite was applied to the section covered with exterior finish cladding and other members.

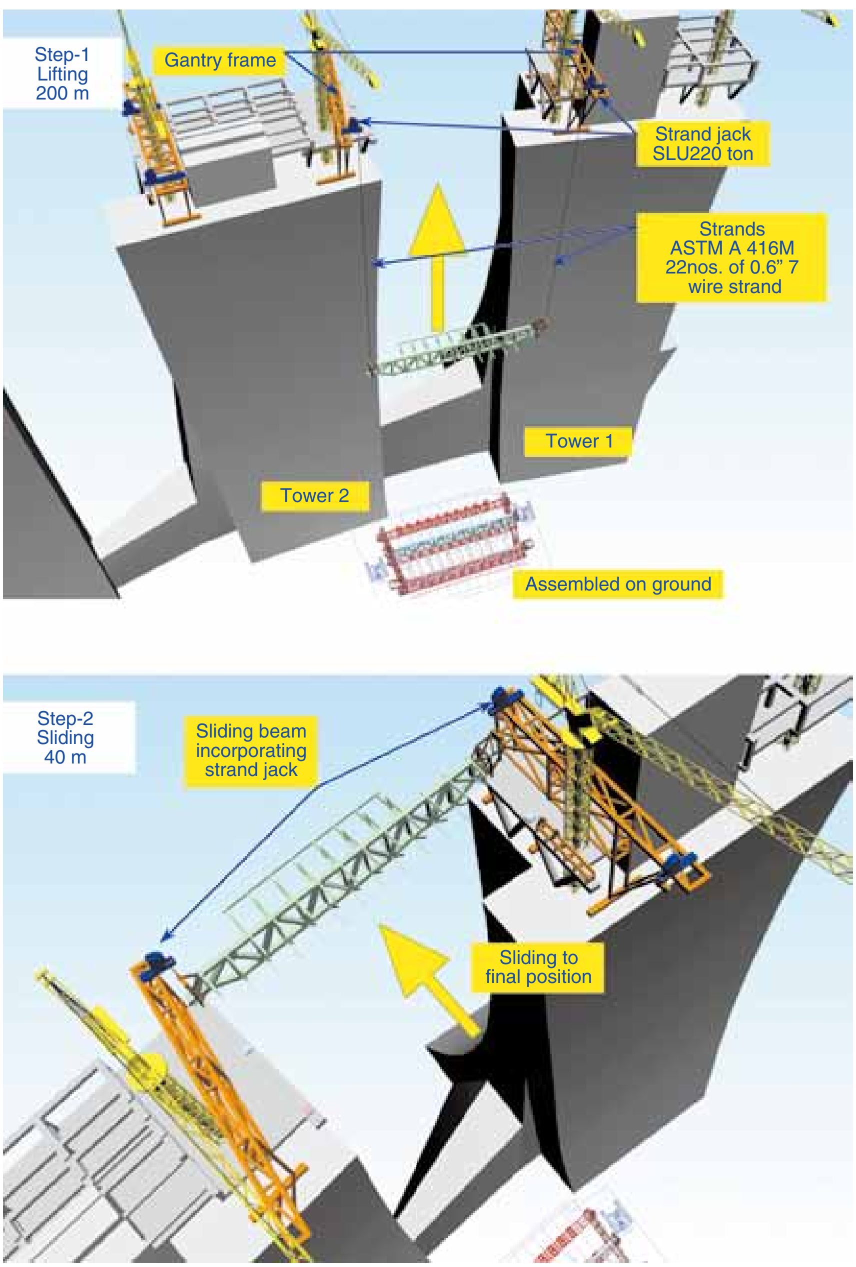
Photo 3 Steelwork fabrication at Yongnam E&C

Photo 4 Trial assembly at Yongnam E&C

Table 1 Heavy Lifting Record

Heavy lifting	Segment No.	Date of lifting (2009)	Segment weight (tons)	Segment length (m)	Reference
Steel truss bridge 1	A3	1-Oct	386	56.8	Photos 5 and 6
	A2	18-Oct	417	54.7	
	A1	29-Oct	324	52.3	
Steel Truss Bridge 2	A6	16-Nov	333	54.0	
	A5	24-Nov	319	51.9	
	A4	6-Dec	255	49.4	
Steel box girder on Tower 3	West	12-Oct	746	73.6	Photo 7
	East	12-Oct	786	75.7	
Steel box girder at north cantilever	NC1	1-Dec	176	5.9	Photo 8
	NC2	9-Dec	195	7.2	
	NC3	14-Dec	182	8.6	
	NC4	18-Dec	129	8.4	
	NC5	23-Dec	99	8.4	
	NC6	29-Dec	70	7.5	

Fig. 3 Heavy Lifting Procedure



Steelwork Fabrication and Erection

Steel structural members were fabricated by Yongnam Engineering & Construction, a local fabricator, and transported to the construction site (Photos 3 and 4).

In erecting the steel-frame structures on Towers 1 and 2, the structural members were lifted one by one using the tower crane to place them at the specified positions. Structural members for the box girder bridge on Tower 3, the two tower-connecting bridges and the cantilevered structure on Tower 3 were pre-assembled into large segments at the ground level in the side of the tower and lifted by strand jack. The large segments thus assembled numbered 3 each for the main girders of the two tower-connecting bridges, 2 for the two main girders of the box girder on Tower 3, and 6 for cantilevered structure. A total of 14 large segments, weighing 4,000 tons in total, were lifted and erected during the three months from October 1, 2009 to December 29, 2009 (Table 1).

The erection work was undertaken by means of a heavy-duty strand jack assembled on a gantry frame installed atop the tower. The segments were lifted to the target height of 200 m. Each segment was lifted at a rate of 15 m/hour, nearly the maximum speed of the jack stroke movement, over a 15-hour period. After each segment was lifted, it was slid into the specified position using a horizontal-pulling jack and was then lowered to its final position by releasing the jack's hydraulic pressure. (See Fig. 3, Photos 5~8)

When planning the lifting work, the assembly position and lift point were decided in a manner that would secure a 1 m-wide gap that would prevent the lifted segments from making contact with the hotel tower during lifting, even if the segment's girder were to move laterally due to wind pressure resulting from the maximum 26 m/second wind velocity assumed in the design.

Safety Measures

Because the construction work for SkyPark routinely took place at heights surpassing 200 m as well as ground with other trades, unprecedented care was taken to secure maximum worker safety. Practically speaking, utmost efforts were thoroughly and repeatedly made to spread over a large working group, including 450 workers and 70 staff during the busiest period, that all workers and staff wear a full harness to prevent falling and carry lanyards to prevent

Photo 5 Heavy lifting of steel truss bridge segment

Photo 6 Sliding of steel truss bridge segment into the specified position

Photo 7 Heavy lifting of box girder bridge segment at Tower 3

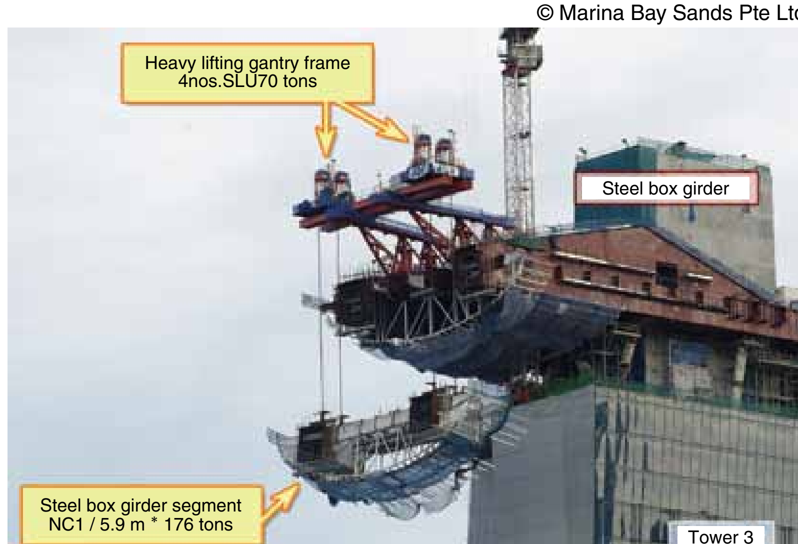


Photo 8 Heavy lifting of cantilever Structure on Tower 3

the dropping of tools.

A detailed procedural manual detailing every type of work was prepared and reviewed by qualified safety officers. The manual not only obtained approval from both the project owner and the consultants but was also examined by every associated manager. And, following thorough discussions, every staff member was well acquainted with the manual. In particular, painstaking risk management control was exerted over work that was forecasted to be dangerous.

Highest Safety Measures Secured for Difficult Work

A noteworthy accomplishment in the construction of SkyPark is the completion of such a huge project, involving difficult construction work, without serious accidents over one million of working hours of labor. This is largely attributable to the united and highly vigorous effort by local enterprise staff, locally recruited engineers and the Japanese staff, efforts that transcended culture and language, to successfully complete the project. Also noteworthy is the presentation to the SkyPark project of the Structural Steel Design Awards 2010 by the Structural Steel Society of Singapore.

Osaka Station

— Large-scale Domed Roof Installed above Station Platform —

By Takayuki Umeki
Senior Manager, Construction Department, West Japan Railway Company

The "Osaka Station Development Project" was a seven-year undertaking that began in May 2004 and finally culminated on May 4, 2011 with the opening "Osaka Station City." The new complex consists of the previously existing station facilities, the North Gate Building located on the north side of the station, the South Gate Building on the south side, the new terminal area on the bridge that connects the two buildings, and a domed roof.

Outline of New Osaka Station City

The area on the north side of Osaka Station, including the Umeda freight terminal, is ranked as the best remaining urban commercial district in Japan and is expected to develop as a new base that will lead the revival of the Kansai area. In October 2003, Osaka City published a document titled "Comprehensive Plan for Osaka Station North District" that indicates the basic direction of urban development in Osaka City (Fig. 1).

Osaka Station City is positioned as a link in town building in the area north of Osaka Station and has been aggressively promoted by the Osaka City government and other administrative organizations, as well as a variety of private enterprises and tenants in the surrounding area.

Specifically, the project's primary emphasis is to improve pedestrian networks with neighboring districts, to enhance the growth of bustling community functions suitable for a gateway district to the Osaka and Kansai areas, and to improve the attractiveness of the area in conjunction with other railway companies. The eventual aim is to dramatically enhance the area's function as a core component of Osaka Station and the surrounding area, in combination with positive efforts by West Japan Railway Company to, among other things, extend operations of the Kyushu and Sanyo Shinkansen super-express lines and to improve and reinforce access to Osaka Station from other urban transport networks.

Basic Goals of the Osaka Station City Project

The project was promoted based on the following four goals.

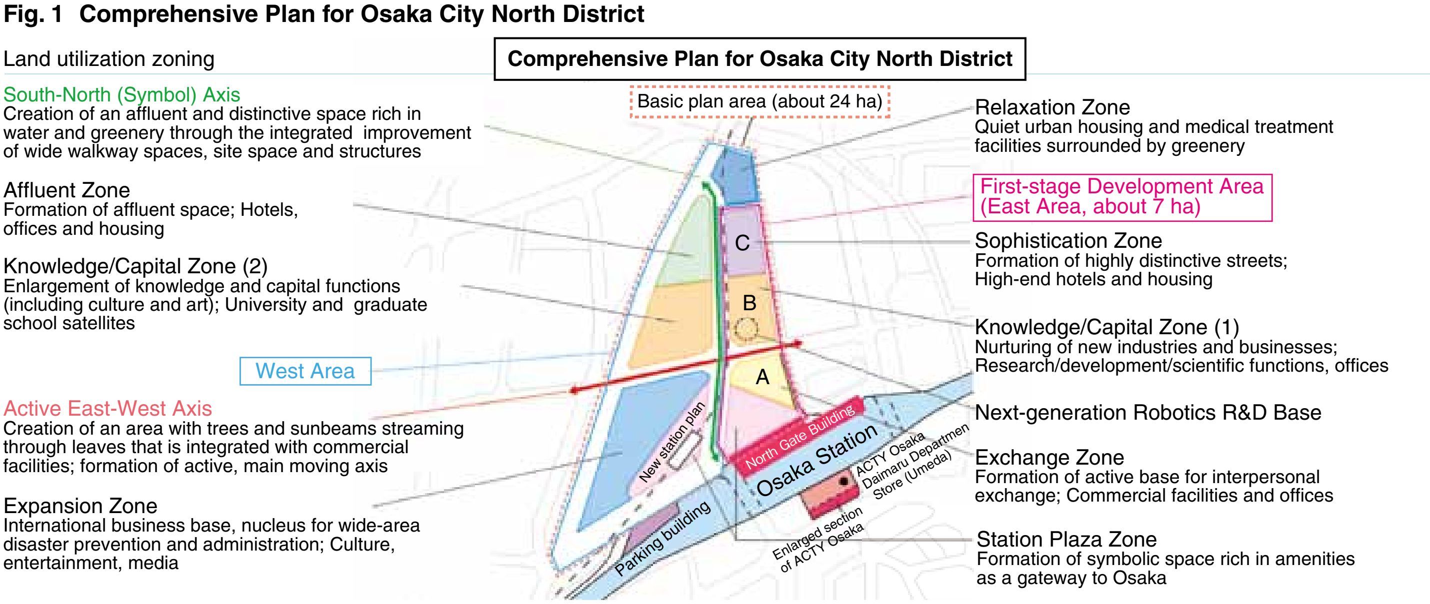
● Provision of Plazas and Passageways

The new south-north connecting passageway was created in the space above the railway tracks to secure smooth moving lines and to improve the ease for the visitors to get around within Osaka Station and its peripheral areas. Further, eight plazas were installed within the station to provide bustling and relaxing places. (Photo 1)

● Improvement of Station Convenience

Various approaches to improving the convenience of the station were devised—in-

Fig. 1 Comprehensive Plan for Osaka City North District



Source: Basic Plan for Town Building at Osaka Station North Area (Osaka City)


Photo 1 Improved station square and passage


Photo 2 Large-scale domed roof on the station building on the passageway bridge


Photo 3 Newly-built North Gate Building


Photo 4 Enlarged South Gate Building

stallation of the ticketing floor on the connecting bridge at the station center, improvement of the concourse within the ticket gate area and provision of totally barrier-free facilities. In addition, a large-scale domed roof that runs about 180 m north to west and about 100 m south to north was installed above the platforms. (Photo 2)

• Installation of New North Gate Building

In order to provide a gateway to the area north of Osaka Station, a new building was constructed on the north side of the station that houses a diversity of urban functions, such as a department store, specialty stores, restaurants, service functions and offices. The building not only offers station functions but also provides plazas and other spaces where people can interact. (Photo 3)

• Enlargement of South Gate Building (Formerly ACTY Osaka Building)

In parallel with improvements to the station plazas, the existing South Gate Building that serves as an entrance to the area south of Osaka Station was enlarged. Work was also completed to improve moving lines and to improve the ease for the visitors to get around to the peripheral areas. (Photo 4)

Design of Domed Roof

Serving as a symbolic structure in the Osaka Station City project, a large-scale domed roof about 180 m in the north-west direction and about 100 m in the south-north direction was installed above the platforms of Osaka Station. A comfortable, attractive station space was thus produced that unifies the North and South Gate Buildings, the station building on the passageway bridge, and the station platforms (Photo 5).

The domed roof is supported at the 12th story of the North Gate Building and by truss framing (east-north framing) that spans the platform. The basic component of the frame is a triangular-shaped space pipe truss (total length: 100 m; 600 in max. dia.), 17 rows of which comprise the domed roof—which is installed in a diagonal form with a maximum inclination angle of 23° and a maximum difference in elevation of 30 m. The roof is finished using folded plates and is equipped with 12 rows of skylights to brighten the interior space under the dome.

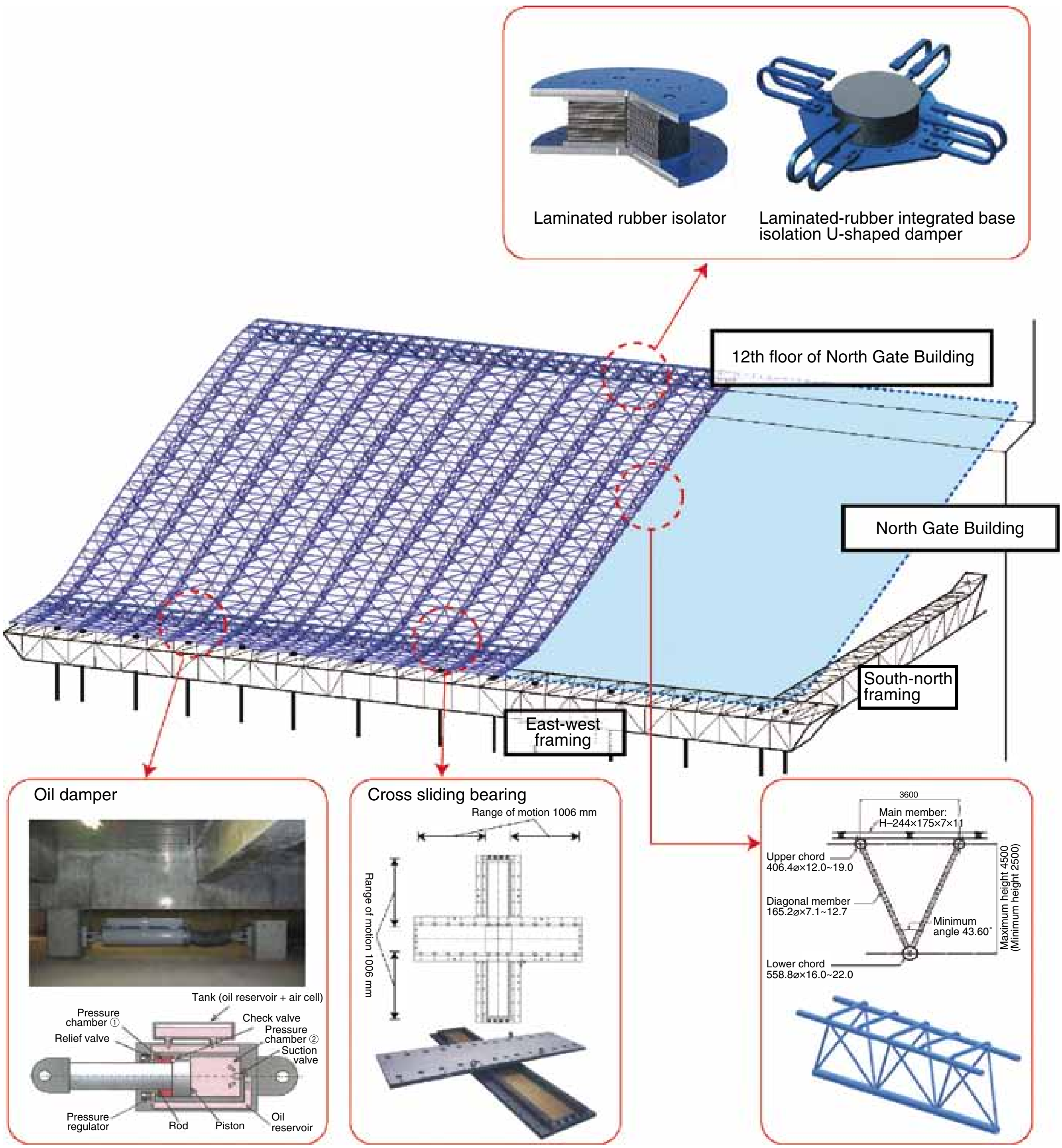
In order to effectively mitigate seismic forces that might work on the domed roof, which has a total weight of 3,500 tons, a base-isolation structure was adopted. A total of 17 laminated-rubber isolators and laminated-rubber integrated base isolation U-shaped dampers were installed on the supporting section of the North Gate Building. Further, 17 cross slide bearings (range of motion: 1 m) and 6 oil dampers were installed on the supporting section of the north-west truss framing so as to avoid transmitting excessive horizontal force to the lower structure during an earthquake. (Refer to Fig. 2)

For the roof finishing material, a heavy-duty coating of silicon denatured epoxy resin was adopted. This coating has a record of wider usage in bridge construction and features a low frequency of maintenance.

Meanwhile, in order to reduce water usage, the rainwater that flows off the roof is collected, via the east-south and north-south trusses, in a storage tank located on the basement level of the North Gate Building and is used as rinse water for toilets.

Photo 5 Domed roof

Fig. 2 Outline of Seismic-isolation Devices for Domed Roof Structure Installed on Platforms



Construction of Domed Roof

In constructing the domed roof, it was necessary to implement the work while allowing the station to function normally. Accordingly, depending on the type of work and in consideration of train operations and passenger safety, construction was executed for about three hours from the departure of the last late-night train until the arrival of the first early morning train. Under these severe restrictions, an effective approach was adopted in which both the framing of the triangular-shaped space pipe trusses and the finishing work were completed one-by-one on the top station building's roof, which had been installed in advance on the passageway bridge, and from which the completed members were slid to both the east and west sides by 7 times to each side. As a result, the domed roof was completed without any serious accidents. The adopted method is introduced in the following.

At first, ground assembly of the trusses was undertaken utilizing the rooftop of North Gate Building lower-floor section that was simultaneously constructed. The trusses were divided into eight structural members, which were ground-assembled. Subsequently, the trusses were moved to the station building on the passageway bridge where they were joined.

As a workspace for joining the moved

trusses, a bent gantry was installed on the rooftops of both the east and west ends of the station building on the passageway bridge, which was built prior to the construction of the center section of the station building. On the bent gantry, the eight divided truss members were joined together; and, at the same time, the folded plates, top glass, coating and other finishing work were completed. At this stage, quality inspection by means of palpation was conducted. (Fig. 3)

Next, each of the completed truss frames was slid to the east and west sides by 7 times while occasionally adding another truss (Fig. 4).

The domed roof trusses were moved to their prescribed position atop the railway by running a truss-loaded transport equipment (TIRTANK; max. 200 tons) on a rail girder placed on the 12th floor of the North Gate Building and on a beam of the east-south framing (Photo 6). For the sliding jack, a continuously operable, center hole-type, high-speed jack (double twin jack; max. 70 tons) was used to complete each sliding job within the short period between the departure of the last train and the arrival of the first train. Meanwhile, in order to understand on a real-time basis the displacement and installation conditions of the trusses during sliding, a measurement control system was developed to improve work safety.

Lastly, employing the bent gantry located on the rooftop of the station building over the passageway bridge, the joining and finishing work were conducted on the three trusses (of 17 total trusses) that were not subject to sliding. Then, the center section of the domed roof structure was built to complete the entire domed roof.

Fig. 3 Assembly of Domed Roof Trusses on the Rooftop of Station Building on Passageway Bridge

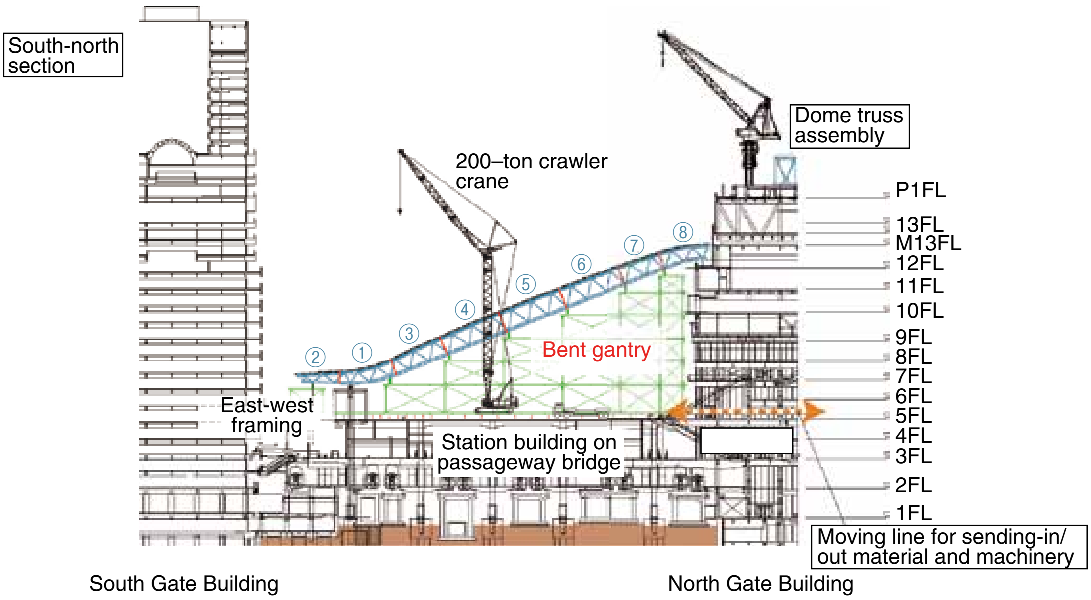
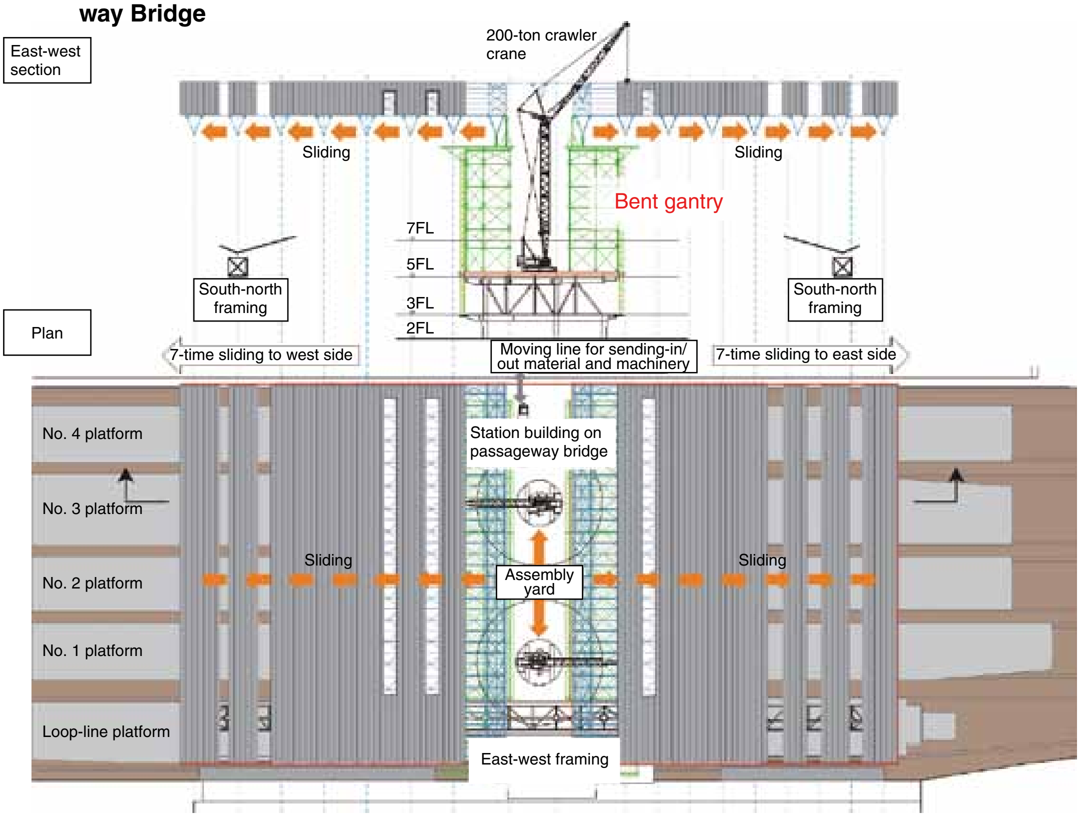


Fig. 4 Sliding Work for Domed Roof Trusses on the Rooftop of Station Building on Passageway Bridge



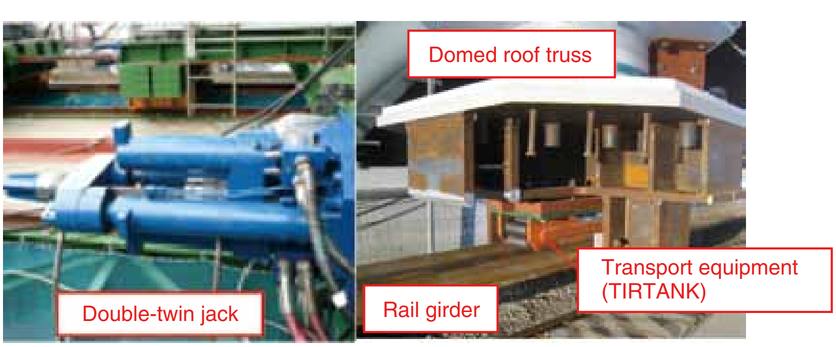


Photo 6 Double twin jack used for truss sliding and TIRTANK used for truss movement

Asahikawa Railway Station

— Structural Design of Open Large-span Station Building —

By Mamoru Kawaguchi and Yushi Aso
KAWAGUCHI & ENGINEERS

Started 15 years ago in 1995, the first phase of construction work on the JR Asahikawa station building, including an elevated railway structure, was completed in October 2010. The station is slated to celebrate its grand opening in November 2011. (See Photos 1 and 2, Fig. 1)

Structural Outline

The building shed of Asahikawa Railway Station is a steel-frame structure built upon a reinforced concrete (RC) elevated railway structure. The shed has a total length of about 180 m, a width of about 60 m and a maximum height of 26.3 m (Fig. 2).

Because the station is located in Asahikawa City, Hokkaido, a prominent area of heavy snowfall in Japan, the treatment of heavy snow accumulation is a well-known and serious problem. In addition, because the plan calls for the efficient utilization of geographical conditions adjacent to rivers in the surrounding area, the roof of Asahikawa Station was planned to be of the snow-retaining type.

Generally, in the construction of station building sheds in Hokkaido, one of the primary requisites is the use of concrete slabs

Photo 1 Full view of Asahikawa Station

Photo 2 Inner view of Asahikawa Station

Fig. 1 Executed Structural Design (Section)

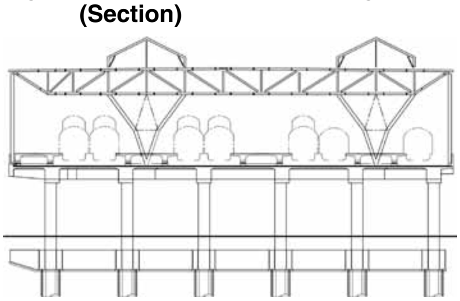


Fig. 2 Structural Outline of Asahikawa Station

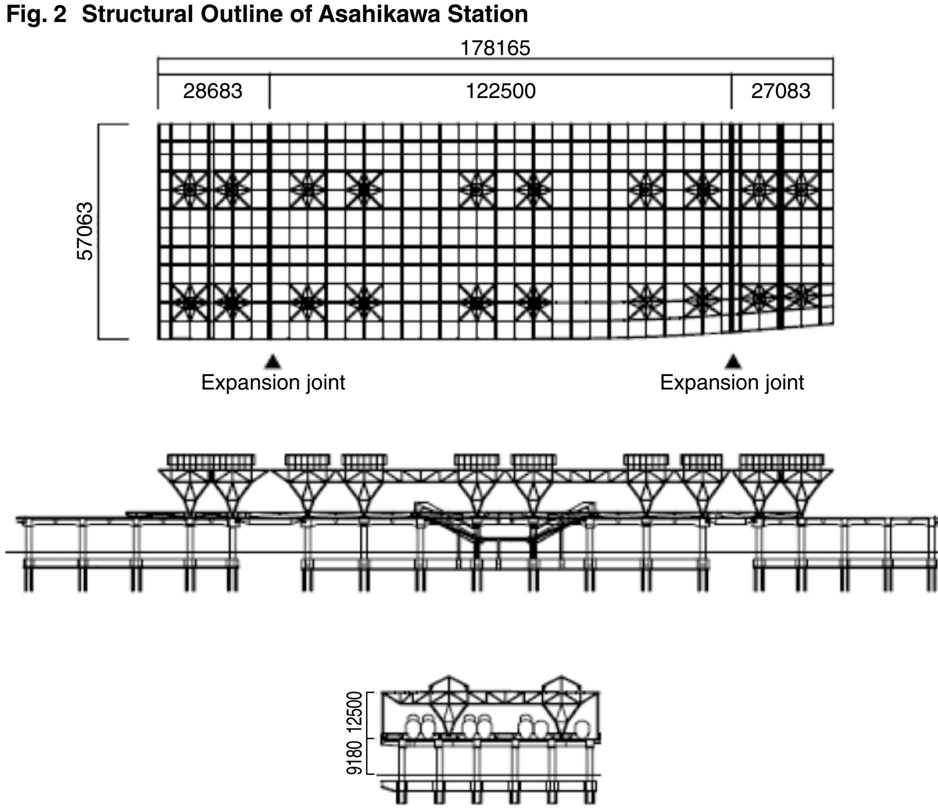


Photo 3 Roof framing

not only to handle the large snow loads that naturally accumulate during Hokkaido's winters but also to prevent water leakage. As a result, the framing that supports a station shed's roof must bear large loads and resist seismic forces over sustained periods of time. To this end, comparatively short columns with large diameters are located together in large numbers in most railway station buildings in Hokkaido with the result that the platforms tend to be dark spaces with limited visibility. In order to realize platforms with fewer obstacles at Asahikawa Station, a structural plan was worked out that secures minimal use of platform columns and greater ceiling height.

To meet the requirements of this structural plan, it was necessary to ensure high strength and rigidity for the roof framing and the underlying support columns, which then led to the adoption of steel-frame trusses with sufficient beam depth and built-up columns called four-branched tubular steel columns.

The shed roof frame is a parallel chord truss structure that is supported by 20 four-branched columns and has a beam depth of 3 m in both the X and Y directions. More specifically, the roof framing consists of upper and lower chords of H250 × 250 and of steel tubes (165.2~216.3 mm in dia.) that constitute the frame's diagonal members and struts (Photo 3). The roof was designed to secure horizontal rigidity by the use of RC slabs (thickness: 150 mm). The building exterior is supported by H-shape pin columns (H400 × 200) that also serve as mullions.

Structural Design of Station Building

In designing the station building, collaboration was required between the civil engineers who designed the elevated railway structure and the structural engineers who designed the shed.

However, in terms of the sequential order of events, completion of the structural design of the elevated railway structure and commencement of the corresponding structural work had to occur prior to the start of the design work on the shed.

This led to a difficulty related to the structural design of the station building. Namely, information about the shed column base reaction force was required for the design of the elevated railway structure and this information had to be supplied to the civil engineers as early as possible in the design stage. In addition, the simpler the load from the shed column base, the better it was for the structural designers of the elevated railway structure. For that purpose, the civil engineers requested of the structural engineers that, in the structural design of Asahikawa Station, they abide by the design condition that "the bending stress not change according to the loading condition at the shed column base." This problem was solved by adopting cast steel pin bearings for the base of the four-branched columns of the shed.

Further, taking into account the temperature-affected load, expansion joints (at two locations) were provided in the area of the elevated railway structure beneath the shed. The expansion joints do not allow the stress transfer in the direction of the railway but do allow stress transfer in other directions. (See Fig. 3) Expansion joints having a similar function were also provided in the area of the shed under which the railway runs.

Detail Designs

● Four-branched Columns

Fig. 4 and Photo 4 show a four-branched column. The main structural members used at the four corners are steel tubes (404.6

Fig. 4 Four-branched Tubular Steel Column

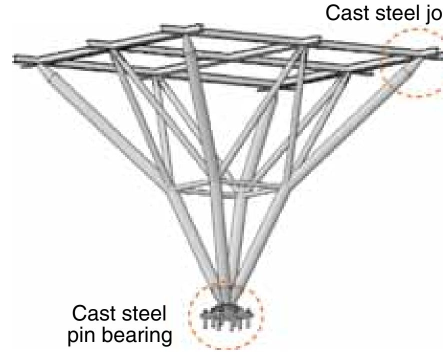


Photo 4 Completed four-branched tubular steel column

Fig. 3 Stress Transfer of Expansion Joint

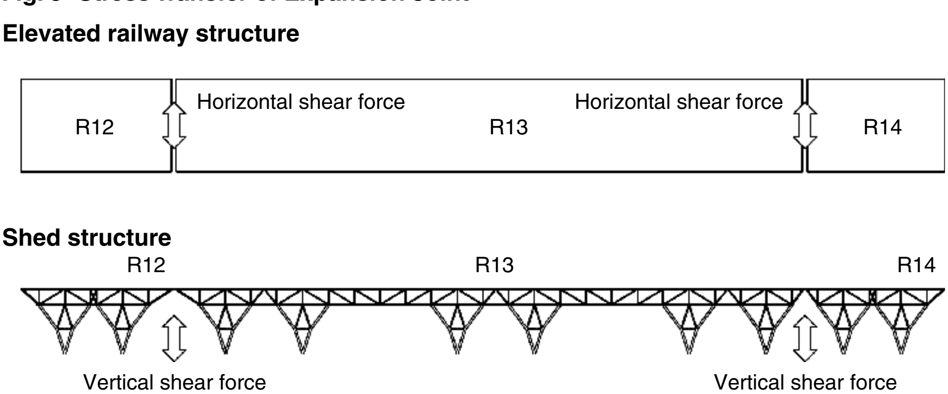
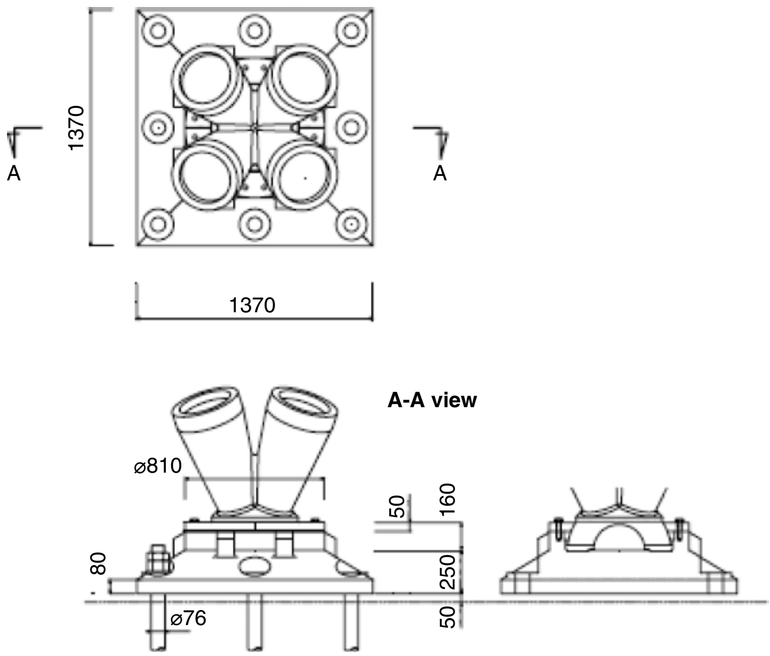


Fig. 5 Cast steel pin bearing



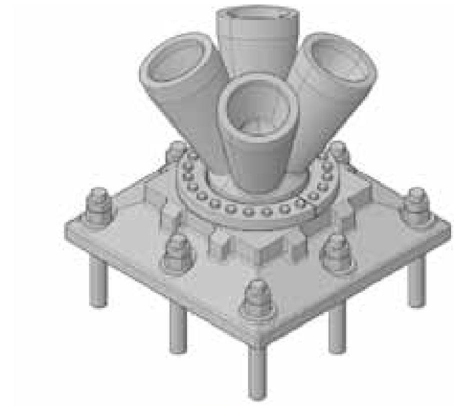


Photo 5 Cast steel pin bearing

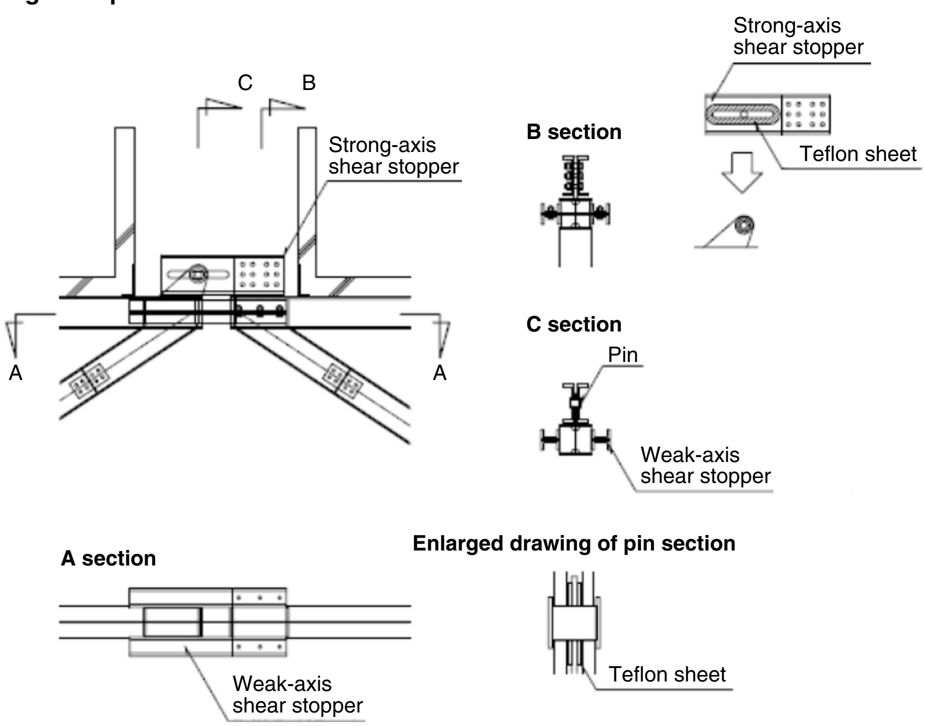
dia. × 30 for the lower structure and 404.6 dia. × 16 for the upper structure); the auxiliary members are steel tubes (216.3 dia. × 25); and the intermediate horizontal joining members are also steel tubes (165.2 dia. × 9). Fig. 5 and Photo 5 show a cast steel pin bearing used for the column bases. The column bases were tightly connected to the elevated railway structure with anchor bolts (8 × M76).

● Expansion Joints

In the elevated railway structure, expansion joints were provided at two locations that do not restrict movement in the direction of the railway as shown in Fig. 2. In the shed, too, expansion joints having similar behavior were provided at corresponding locations so that the joints would follow the movement of the elevated railway structure to avoid any adverse effect on the shed. (See Fig. 6)

In order not to restrict axial-direction movement between trusses, a long hole was drilled in the axial direction to connect them using pins (65 dia.). A detail design was adopted in which the strong-axis shear force is transferred via the pin and the weak-axis shear force is transferred via the weak-axis shear stopper that extends from the truss end in a cantilever beam state.

Fig. 6 Expansion Joint Installed on Shed Roof



Open and Bright Station Building

A significant task in the structural design work discussed earlier was to construct, in one of Japan's prominent areas of heavy snow and in a town with a long winter season, an open and bright station building that would accommodate large crowds of people. At the same time, another large task was imposed from a civil engineering perspective on the structural design work—the realization of a column base that would suppress bending stress deviation in the elevated railway structure. We believe that these two tasks have been successfully hurdled by the adoption of four-branched columns and cast steel pin bearings.

ION Orchard

— Mega Steel Truss Structure Spanning MRT Station —

By Kazushi Yamashita (Deputy General Manager) and Kelvin Teh (Quality Manager)
Penta-Ocean Construction Co., Ltd.

Introduction, Accessibility and Facilities

Seated at the gateway to Orchard Road, ION Orchard is a mixed development featuring a retail podium and a residential tower (Photo 1).

ION Orchard brings together the world's best loved brands for their flagship, concept and lifestyle stores within one development over eight levels of intelligently designed shopping space—four levels above ground and four levels below.

ION Orchard offers to visitors a unique shopping experience of retail, F&B (food/beverage) and entertainment stores, which include six of the world's top luxury brands with their signature flagships in duplex units fronting Orchard Road, international brands, and popular high street fashion and lifestyle stores carefully selected for their strong branding and innovative retailing concepts. In addition to the extensive stable of brands, an extensive food hall will offer to visitors a myriad of food choices ranging from local favorites to international cuisine.

ION Art, a dedicated programme, introduces new and multi-media art into the integrated mall experience and offers the best of Singapore and other Asian modern and contemporary art and design of established and emerging artists and designers. This includes a 5,600 sq ft gallery space within the mall—the largest of its kind in Singapore—that houses international and local exhibitions and displays of art, design and new media.

ION Sky, an observation deck, is an event and F&B space. ION Sky is located on L55 and L56 and at an impressive 218 m, the tallest point on Orchard Road, giving visitors a commanding 360 degree view of the city.

With more than 330 shops spread over a net lettable area of 624,440 sq ft on eight levels of space, including four built underground. The fifth to eighth floors are taken up by carpark lots and M&E (mechanical and electrical) plant rooms. (Photo 2)

Integrated with Orchard MRT Station and connected to the surrounding developments, direct access is provided to the Orchard MRT Station below. A new underground pedestrian mall across Paterson Road to Wheelock Place completes the underground pedestrian network at the Orchard Road-Paterson Road junction.

Orchard Residences is named for its most coveted and strategic location at the gateway to Orchard Road. It is also Orchard Road's tallest landmark building, a stature and distinction approved by the authorities. A total of limited 175 exclusive, super luxury apartments housed in the district's tallest and most architecturally-definitive landmark aim to offer a lifestyle of timeless elegance and privacy in the midst of the vibrant city below. Orchard Residences sets unparalleled benchmarks in every aspect of luxury living by way of its all-encompassing design features that maximize its views and its attention to every lifestyle need of the most discerning.

Construction Challenges

The main contractor was given challenging tasks to turn the iconic ION Orchard from vision to reality. These challenges include:

- Building above and beside an existing live MRT Station (with loading constraints)
- Constructing an underpass to connect ION Orchard to Wheelock Place below, an existing busy road (keeping same number of lanes during diversion at dif-

Photo 1 Full view of ION Orchard development

Project Outline

- Name: ION Orchard
- Location: 2, Orchard Turn, Singapore 238801
- Construction floor area: Approximately 160,615 m^2
- Building height: 218 m
- Usage: Retail mall and a residential tower (175 super luxury apartments)
- Foundation: Barrette piles and bored pile with steel plunge in columns
- Podium super-structure: Steel mega trusses, composite mega columns and composite metal deck slab
- Tower super-structure: Precast and reinforced concrete
- Method of construction: Top-down construction from basement 1 level
- Project status: Completed in May 2009 (retail) and Oct. 2010 (residential)
- Client: A joint venture between CapitaLand and Sun Hung Kai Properties
- Architects: Benoy Architects (Hong Kong) and RSP Architects Planners and Engineers Pte Ltd (S'pore)
- Main contractor: Penta-Ocean Construction Co., Ltd.

(See Photo 1)

Photo 2 More than 300 shops are spread over eight levels of space including four levels underground (CG)

ferent work stages)

Construction Strategy and Innovation

With the above challenges and constraints in mind, the following construction strategy and innovation were employed:

- Diaphragm wall was constructed as permanent wall for basement and underpass.
- Top-down construction method from basement 1 level was employed so that superstructure works and basement works can proceed concurrently. This method also eliminated the need for temporary steel struts for basement construction as the floor slabs were designed to support the basement walls, thus saving time and resources.
- Mega steel trusses spanning across and above the MRT Station were constructed for levels 5 to 8 due to the station's loading constraints. Composite mega columns were constructed to support these mega trusses which in turn were supported by huge barrette piles that were constructed as the foundation and permanent basement columns.
- The podium's superstructure was constructed using steel structure and composite metal decking system. Dismantling of formwork is was not required, and slab was constructed on metal deck, which thus improved safety and reduced construction time and environmental impact.
- The tower block was constructed on a 6-day per floor cycle using precast shear walls, beams and planks including precast staircases. Table forms were not required, and thus internal wet trades and M&E services could proceed immediately when each floor was constructed.

(Refer to Fig. 1)

ION Orchard's Mega Truss Construction

The unique steel construction process in this project is the mega truss construction spanning across the MRT Station. The stage-by-stage processes relating to this construction are emphasized as follows:

- Barrette pile and column construction
- Mega column construction
- Mega truss assembly
- Heavy lifting of mega trusses
- Composite metal deck slab construction

(Refer to Fig. 2)

Barrette Pile and Column Construction

Barrette piles and columns were used to address the requirement for large singular point loads from individual mega columns for mega trusses and for the 56 storey-high residential tower.

A barrette pile configuration consists of several barrette cages, a barrette beam to connect these cages and the barrette column placed on top of barrette beam.

The construction method is very similar to the diaphragm wall construction in that, upon excavation to the required depth, reinforcements were installed and then cast using tremie pipes, allowing concrete G50 to be filled from bottom up.

The width of barrette piles are generally 1.5 m with lengths from 6 m to 9 m and

Fig. 1 Construction Strategy and Innovation

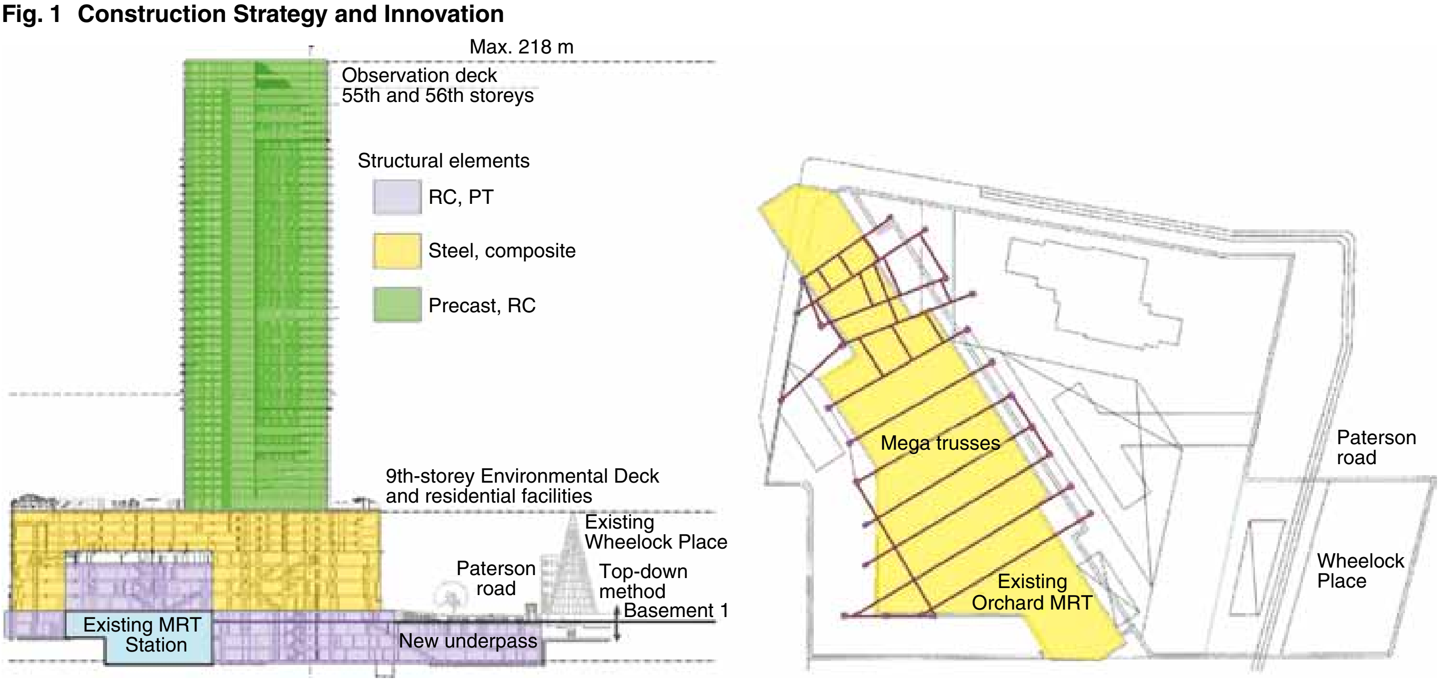


Fig. 2 Mega Truss over MRT Station

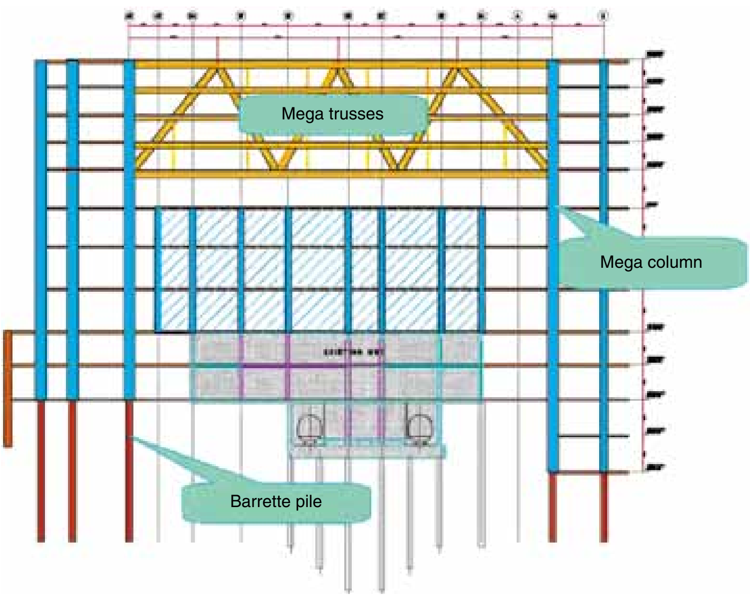
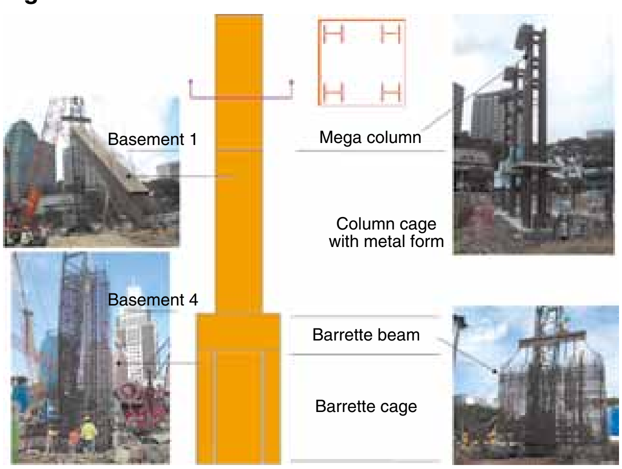


Photo 3 Mega column construction

Fig. 3 Barrette Pile and Column Construction



depth ranging from 43 m to 82.5 m. The width of the barrette columns to support mega columns is 1.5 m, and the lengths ranging from 1.5 m to 3 m. Total lifting weight ranged between 50 tons to 135 tons. Concrete for each pour ranged from 430 m^3 to 1,130 m^3. Sonic tests were carried out to confirm the pile integrity before excavation to expose the barrette columns. (Refer to Fig. 3)

Mega Column Construction

Mega columns of sizes 2 m x 2 m, 1.5 m x 2 m and 1.75 m x 2 m, and 2.4 m in diameter composite (each containing 4 universal columns of weights 162, 202, and 283 kg/m) were secured to the top of barrette column.

The mega columns were constructed in 3~4 segments up to the 9th storey. The height of the tallest mega columns was approximately 37.7 m. (Photo 3)

Mega Truss Assembly

There were a total of 14 mega trusses constructed with the longest and heaviest truss, 508.93 tons in weight and 75.63 m in length, to span across the MRT. The heaviest segment for this truss was approximately 60 tons with a length of 23.73 m.

Due to existing structures above the MRT, the assembling of mega trusses could not be done at ground level. Therefore, a temporary platform with temporary column supports (totaling 2,500 tons of steel) was erected at level 3 (due to constraint for craneage requirements for the lifting of steel sections).

Five floors of steel trusses were assembled on this temporary platform, and the completed trusses together with its associated floor beams were checked thoroughly before allowing the jacking up to their final level. (Refer to Fig. 4 and Photo 4)

Photo 4 Mega truss assembly (temporary platform)

Fig. 4 Mega Truss Assembly

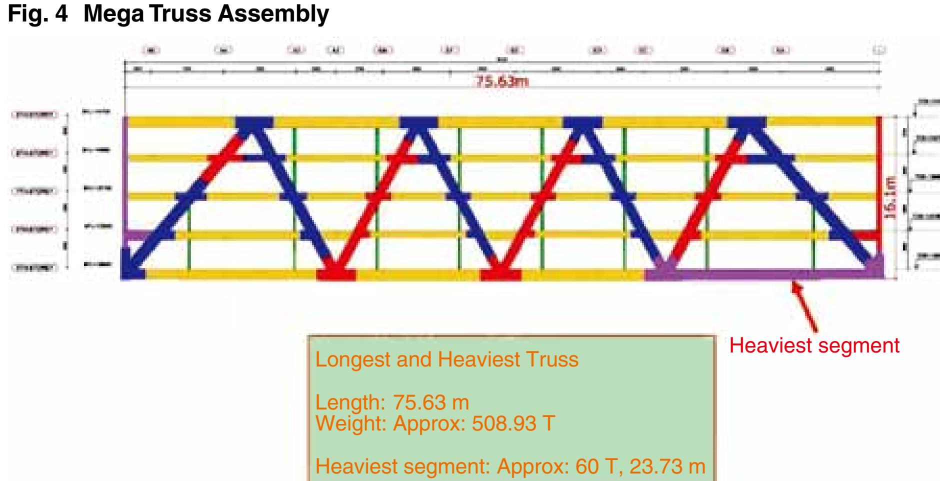
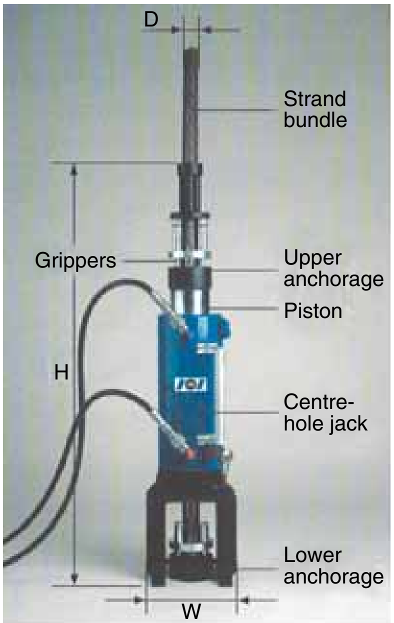
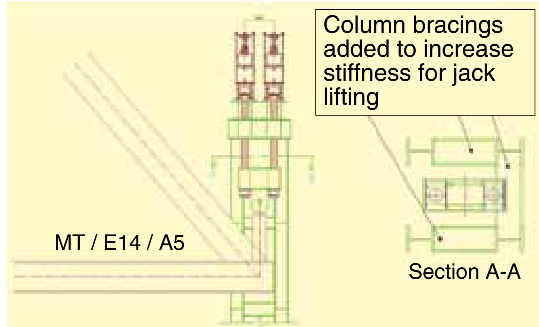


Fig. 5 Mega Truss Heavy Lifting Equipment and Process





Heavy Lifting of Mega Trusses

A heavy lifting specialist was engaged to lift the completed mega trusses from level 3 to its final position at level 5 due to limitations by craneage facilities. This was achieved using a hydraulic strand jacking system.

The main components of this hydraulic jacking system are the motive unit (consisting of a hydraulic centre hole jack and the lower and upper anchorages which is attached to the jack piston), the tensile member (consisting of 7 wire pre-stressing steel strands with 15 mm in nominal diameter) with the anchorage for the load, the hydraulic pump and its controls.

During lifting, the jack was extended, causing the individual strands of the tensile member to be gripped by the upper anchorage and thus to be moved upwards. At the start of the piston's downward movement, the strands were immediately gripped by the lower anchorage, while at the same time the upper anchorage opened. The load was thus moved in a step-by-step process. The unique self-gripping concept of the motive unit anchorages provided a maximum level of inherent safety.

(Refer to Figs. 5 and 6, Photo 5)

Composite Metal Decking Slab Construction

The composite metal decking floor slab is a mixed construction system employing a steel sheet which serves as shuttering for concrete and reinforces the slab partially, replacing the tensile reinforcements. This system was applied throughout the podium superstructure slabs including the mega truss area.

Steel profiles are fixed onto the steel floor beams and serve as a work platform, thereby allowing trafficking in good working and safe conditions before the concrete is laid. Once the profiles have been installed, the underside of the floor becomes watertight and offers a clean finished appearance.

The shape of the ribs sets the steel profile securely in the concrete. All that was done was to finish off the slab with a welded mesh. This system eliminated the use of reinforcement bars and reduced concrete usage.

Fig. 6 Mega Truss Work before and after Lifting

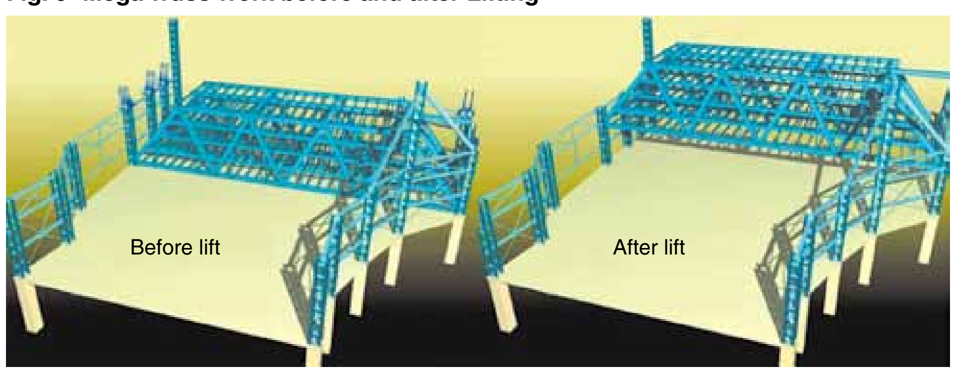


Photo 5 Mega truss work before and after lifting

Special Report

Great East Japan Earthquake
— Proposal of Steel-structure Technologies and Methods for Use in Restoration and Reconstruction —

In order for the earthquake-stricken districts of Japan to regain their former vitality and a sense of safety, it is urgent that a vision for their restoration and reconstruction be found.

For its part, the Japanese steel industry has accumulated steel-structure technologies and methods with excellent disaster-preventive, economical and environmentally friendly performance characteristics. Capitalizing on these technologies, the industry believes that it can contribute to the pressing task of reconstructing and restoring towns and infrastructures so that they are resistant to disaster.

The distinctive features of steel structures are: the high strength and good workability peculiar to steel products, ease of transport, stable mass supply of shop-manufactured structural members, and precise and highly reliable product dimensions and quality. By making the most of these features, steel structures offer the advantages of: reduced construction terms made possible by on-site construction, excellent landscaping performance due to a high degree of freedom in design, and being able to create flexible space. Further, the combined use of concrete, timber and other materials allows for the creation of safer structures.

Under current conditions, the Japan Iron and Steel Federation is offering proposals for the application of steel-structure technologies and methods in restoration and reconstruction projects that are now being worked out, typical of which are the following projects (refer to the figure below):

- **Improvement of disaster-resistant public and emergency facilities**
  ① Seismic- and tsunami-resistant podiums and steel-structure emergency buildings; ② Highly seismic-resistant school facilities of steel construction
- **Rapid restoration of seismic-resistant housing**
  ③ Steel-framed houses with shorter construction terms
- **Improvement and early restoration of coastal and port/harbor facilities, measures against earthquakes and tsunamis**
  ④ Port/harbor renewal using steel products; ⑤ Seismic reinforcement of piers, seawalls and breakwaters using steel products; ⑥ Reinforcement of existing bridge piers using steel pipe and sheet piles; ⑦ Seepage seawall using steel pipe and sheet piles; ⑧ Measures against liquefaction of ground inside coastal seawalls
- **Improvement of emergency bases of operation allowing quick disaster response**
  ⑨ Floating emergency centers (Megafloat: floating steel structure)

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C O N T E N T S

COVER
(*upper left*) Domed roof of Osaka Station City (for details, see page 8); (*upper right*) Open and bright platform at Asahikawa Station (page 12); (*lower left*) SkyPark in Singapore (page 4); (*lower right*) ION Orchard in Singapore (page 15)

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