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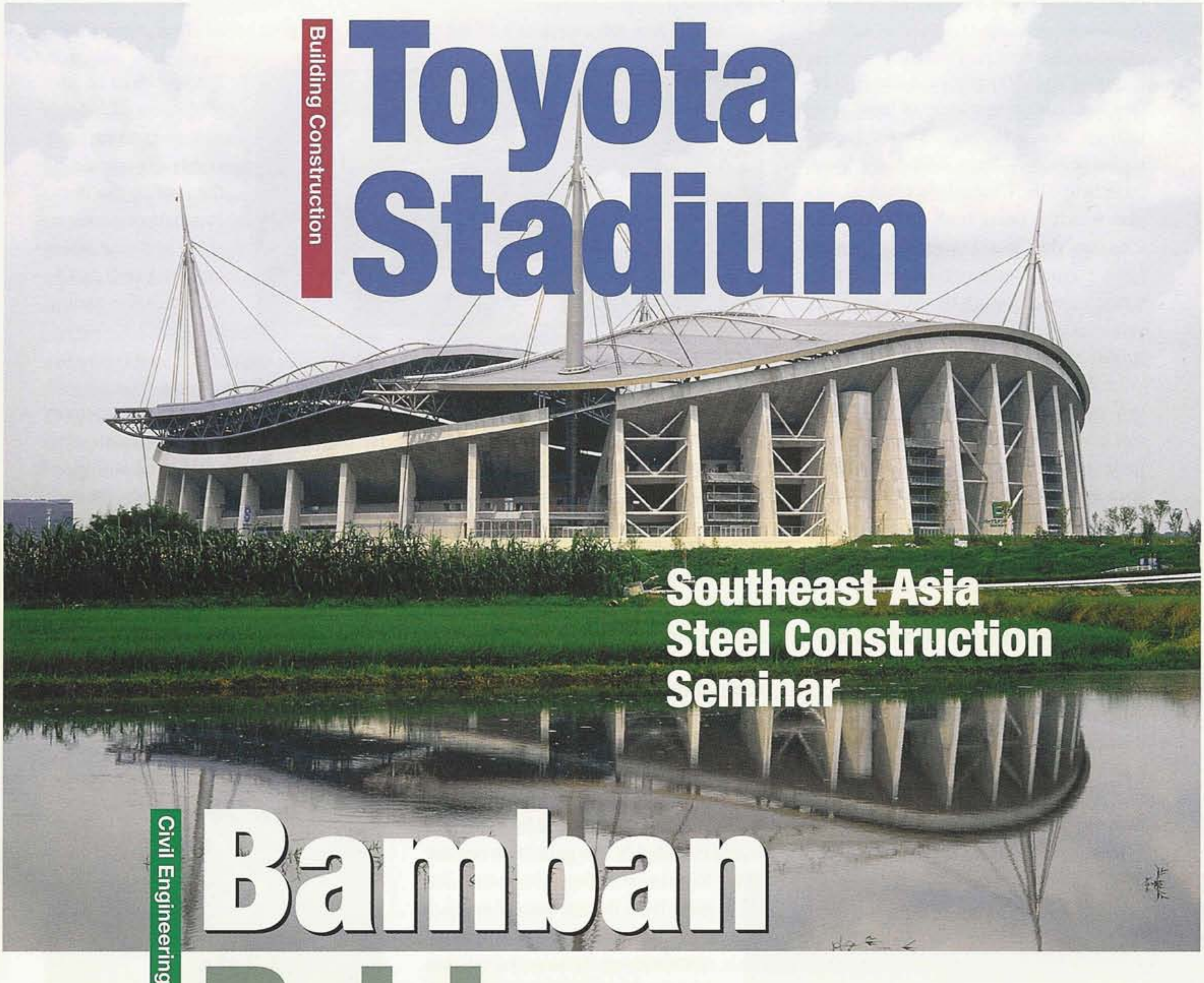


Kisho Kurokawa Architect & Associates

Building Construction

Toyota Stadium

Southeast Asia Steel Construction Seminar

Civil Engineering

Bamban Bridge in the Philippines

Toyota Stadium
—Structural Systems—

By Ikuhide Shibata
Ove Arup & Partners Japan Ltd


Toyota City

Night view of Toyota Stadium

Toyota City, a district of Aichi Prefecture, is neighboring a series of large-scale projects planned to revitalize the central region of Japan—Expo 2005 Aichi, located in Seto City; Chubu International Airport which is being built off Tokoname City; and the Chuo Linear Superexpress Line. Toyota Stadium, a symbolic structure commemorating the 50th anniversary of Toyota City, was built as a forerunner among numerous projects in the area. It is a domed multipurpose stadium with a seating capacity of 45,000 and is used for international sporting competitions such as soccer, rugby and American football, as well as various other events.

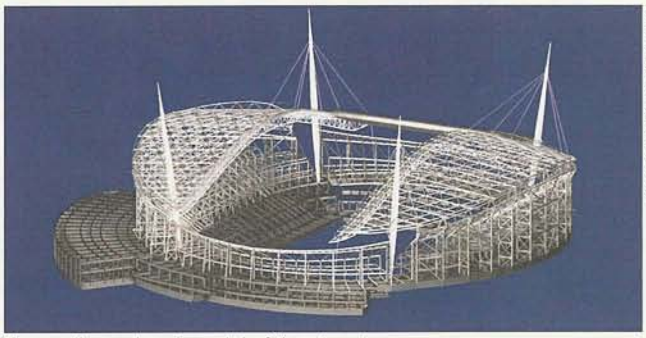
Form and System

The form and system of Toyota Stadium have been devised so as to provide a space that is ideally suited for the natural grass turf, the spectators, and the players.

The stands are divided into four independent structures that comprise the north, south, east and west sides of the stadium. The east and west stands rise higher than the north and south stands, thereby giving an undulating appearance to the stands as a whole. There are two purposes for this configuration. One is to draw spectators into the east and west stands which are most suitable for watching soccer games. The other is to allow sunlight and ventilation onto the natural turf pitch by restraining the height of the north and south stands. With a maximum inclination of 38 degrees, these spectator stands create a theater-like atmosphere.

The stadium's enormous suspended roof, together with the layout of the stands, plays a very important role in securing the amount of sunshine needed to maintain a natural turf pitch and to create an open space with excellent visibility. This 40,000 m² roof is supported by four giant masts installed at the gaps between the four stands without obstructing the view from the spectators' seats.

The retractable roof is made of membrane materials and retracts into the upper section of the north stands when opened. When the entire field needs to be covered, the roof unfolds all the way to the south stands. By containing the roof in the north stands, necessary sunshine and ventilation can be provided to maintain the natural turf.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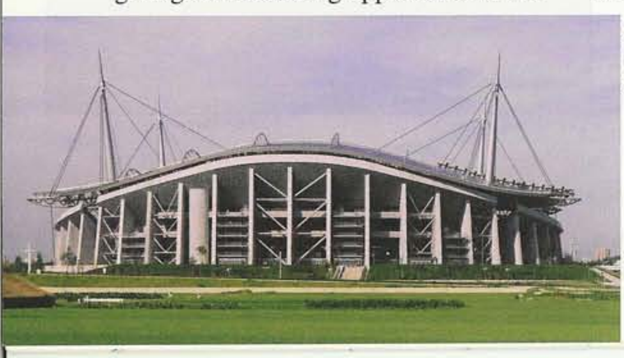
Three-dimensional model of the structure


Toyota City

East-side view

Stand Structure

The spectator seating is divided into upper and lower levels with a plaza area separating them. The upper level is divided into four independent structures, one each on the north, south, east and west sides. These, in turn, are separated by the masts that support the roof.

In order to provide the design with the maximum flexibility, steel structures were used that consisted of seismic-resistant steel frame bracing. Energy-control braces, made of extra low-yield

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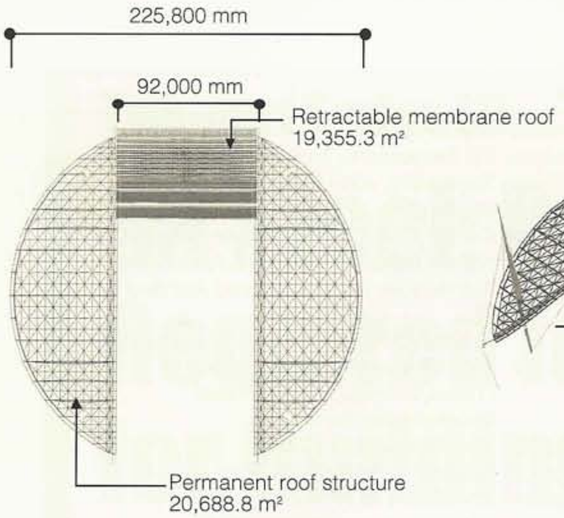
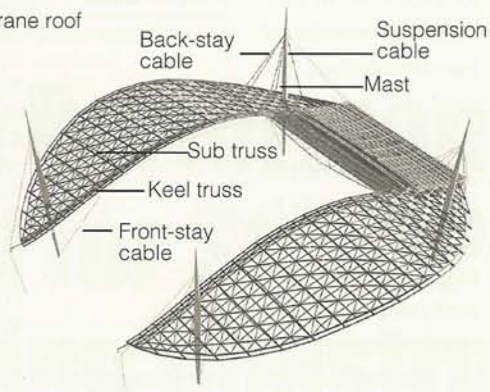


Plan view of the roof



Perspective view of the roof

point steel, were selected to absorb seismic energy during earthquakes.

Cable-suspended Roof Structure

The fixed part of the roof, supported by cable-suspended structure, consists of four masts with a maximum height of 90 m located at the four corners of the stadium, two 250 m long, 6.25 m deep keel trusses, and about 60 coated, parallel wire strands.

One of the significant features is the use of the four giant masts and a three-dimensional arrangement of stay cables. The primary elements to stabilize the roof are the in-plane stay cables that are aligned on the trusses and are intermediately supported by the masts inclined outward by 7.5 degrees. Then back-stay cables from the top of the masts are anchored either to the top of the stands, or through the end of the keel trusses to the stand footings.

In addition, stay cables are aligned on the front section (from keel to mast footing) and initial tension is introduced into the cable so as to prevent instability in the roof structure due to a loss of tension in the suspended cables when struck by wind gusts or by earthquakes.

Pivot bearing of the mast

Mast

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Mast Structure

The masts located at the four corners of the stadium are spindle-shaped, built-up steel tubes with a maximum outer diameter of 3.5 m. They were manufactured by bending and weld-joining steel plates (maximum thickness: 70 mm). Each of the north-side masts, which is made of SA440B steel and supports the retractable roof, carries approximately 60 kN long-term axial force as the reaction to the roof including the deadweight of the cables. Each of the south-side masts, HT355B steel, carries approximately 40 kN.

At the location where the masts go through the roof, adequate clearance is provided so that the roof and the masts do not interfere with each other.

Further, pivot bearings are used in the footings of the masts so as to allow omnidirectional rotation. Therefore the masts stay at the 7.5 degree inclination by the balance of the interdependent cable forces only.

Pivot Bearings of the Mast

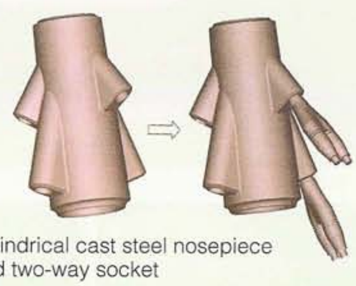
The pivot bearings of the masts consist of upper and lower cast steel shoes. The force transfer is achieved by direct bearing pressure that transfers compression and shear forces of the mast. The mast will not go into tension. The contact surfaces are made of the semi-sphere concaving upward with different radius. By making the upper shoe's sphere radii 5 mm larger than the lower shoe's sphere radii, the upper shoe can rotate relative to the lower shoe. The maximum allowable rotation of this bearing detail is ±2.5 degrees.

Parallel Wire Strand Cables

For the cables, a maximum of 499 galvanized steel wires (1,600 N/mm² grade and 7 mm in diameter) are bundled to form each strand which is then coated with polyethylene. The wires at the end of each cable are unbundled and cast into a socket cone filled with a cast zinc-copper alloy. Thus forces exerted on the cables are transferred from the steel wires to the zinc-copper alloy by adherence between them and from the zinc-copper alloy to the inside of the socket cones by surface pressure and friction.

Cylindrical Cast Steel Nosepiece and Two-way Socket

Ten cables are connected to the top of each mast. Each cable measures about 140~200 mm in diameter and transfers a long-term tension force of around 5~7 kN and a maximum force of 11 kN during earthquakes. To smoothly transfer the cable reaction forces to the mast and to do this with simple low-cost joints, two cables are integrated into one using a cast steel member called a two-way socket that weighs about 6 tons. A joining system that uses bolts with inverse threads is employed to join the two cable end sockets with the two-way socket.



Cylindrical cast steel nosepiece and two-way socket

Cylindrical cast steel members (weight: about 40 tons each) with noses are used to affix the two-way sockets to the masts by means of a bearing pressure connection with a nut. The threaded tops (diameter: about 45 cm) of the sockets are inserted into the noses and are fastened from the inside using nuts (diameter: about 60 cm). This causes each nut's front surface to serve as a bearing pressure surface and thereby to transfer force from the cable to the mast.

Retractable Roof with Air-inflated Membrane Structure

The membrane-type retractable roof spans between the keel trusses of the fixed roof sections. In contrast with conventional movable domes, this roof is normally retracted in the open position above the north-side stands to provide sunshine for the natural turf. The roof covers the north stands when retracted, but covers both the north and south stands as well as the entire field when fully extended. About one hour is needed to open or close the roof.

This movable system uses self-propelled rack-and-pinion bogies, folding trusses that retract, and a membrane cover (13.5 m × 73 m) located between the trusses (length: 90 m; height: 6 m) that changes shape when being opened or closed.

The operating speed of the bogies is controlled by means of inverters and each bogie is equipped with a fail safe mechanism that engages an electromagnetic brake to stop it during emergencies.

PVC polyester was selected as the membrane material for the retractable roof considering the fact that the surface will not be exposed to the UV when parked at the standard position and also the required flexibility of the membrane. An inner pressure of 20 mmAq is used to stabilize the membrane under normal conditions during movement and a pressure of 10 mmAq is used when extended. The pressure is controlled by blowers and pressure valves.

In addition, springs with a stroke of 60 cm at a cycle of 4 seconds are installed along the edges of the trusses to absorb the displacement between the fixed roofs and the trusses during roof operations and earthquakes.

Large-scale Movable Screen

A large movable screen is suspended beneath the keel trusses with a tension truss frame. It is normally moored to the north stands but moves to the front of the stands during multi-purpose events. The screen unit can be raised, lowered and rotated as necessary.

Project Data

Project name	Toyota Stadium
Location	7-2 Sengokucho, Toyota City, Aichi Prefecture
Client	Toyota City, Aichi Prefecture
Building type	Stadium
Design	Central Park Promotion Office, Toyota City Kisho Kurokawa Architect & Associates Architecture: Kisho Kurokawa Architect & Associates Structure: Ove Arup & Partners Japan Ltd.
Contractors	Joint venture of six companies (Taisei, Shimizu, Yahagi, Taikei, Toyotasouken,Sanei)
Design period	April 1997 to July 1998
Construction period	September 1998 to July 2001
Scale	Site area: 116,777.44 m^2 Total floor area: 105,830.46 m^2 Maximum height (mast) : Design GL + 92.7 m Maximum height (roof) : Design GL + 55.77 m Stories: Four stories above ground, two stories below ground Seating capacity: 45,000 Parking capacity: 208

Toyota City

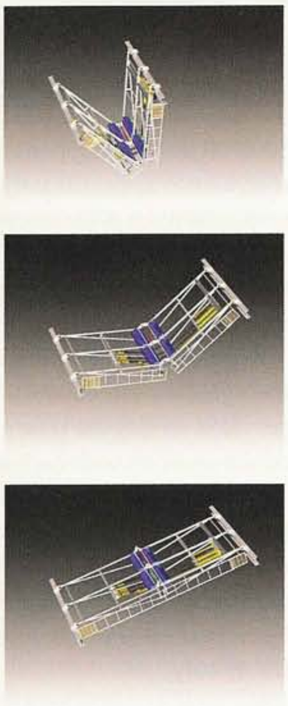
Inner view of the stadium

Kisho Kurokawa Architect & Associates

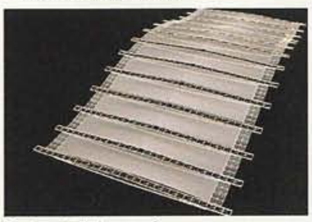
Fully-closed state

Toyota City

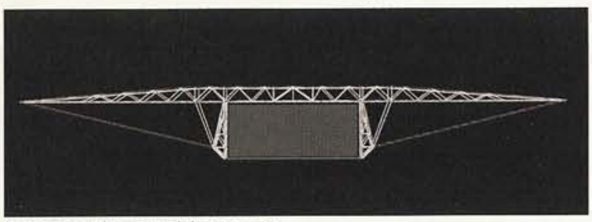
Fully-opened state



Folding truss



Retractable roof



Large-scale movable screen