

# World's Largest Cricket Stadium

Construction of the structure's large precast concrete elements required microlevel design verification, planning, and monitoring

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The intricate geometry of the portal frame rising from the podium level of Motera Stadium, Ahmedabad, India, is defined by the architects' intent to provide a 360-degree view of the field of play from the podium level. Located 12 m (39 ft) above nearby streets, the podium level serves as an elevated plaza providing traffic-free pedestrian flow to and from the stadium's lower and upper seating bowls, each with a capacity of about 50,000. To ensure rapid entry to and exit from the stadium for spectators, the podium level is accessed from street level via two massive pedestrian staircases.

Motera Stadium was designed by the Australian studio of the sports-architecture firm POPULOUS. As with most stadiums, Motera Stadium's structure consists of exposed concrete. Due to the repetitive nature of the stadium's structural elements, precast concrete was chosen to ensure rapid construction and high-quality finishes. While the design team discretized the precast elements, a strong emphasis was placed on minimizing the number of elements and their joints, and this resulted in large and heavy elements with complex, asymmetrical geometries. These features complicated the casting, transportation, lifting, and erection of the precast elements in the portal frames, necessitating the development of innovative structural designs for rigging the elements during various stages of erection. For each stage, the precast elements were meticulously analyzed, designed, and detailed accordingly.

## Structural System

The stadium structure comprises:

- Lower and upper seating bowls;
- A podium level with entry/exit staircases for spectator circulation and concessions and access to the upper and lower bowls;
- An intermediate (upper ground) level below the podium level, providing restrooms; and

- Vomitory staircases for accessing the upper bowl from the podium level.

The oval stadium structure is divided into six segments by radial expansion joints (Fig. 1). Expansion joints also isolate the ramps from the podium level, and a circumferential expansion joint at the junction of the podium and lower bowl isolates the upper bowl from the lower bowl. Twin columns support the structure on either side of each radial joint up to the podium level. At the top of the upper bowl, circumferential beams rest on corbels on the primary radial beams, resulting in a roller boundary condition for each of the circumferential beams at the radial joint. The upper-bowl columns have corbels near the podium level, supporting the lower bowl's radial beams with a roller boundary condition.

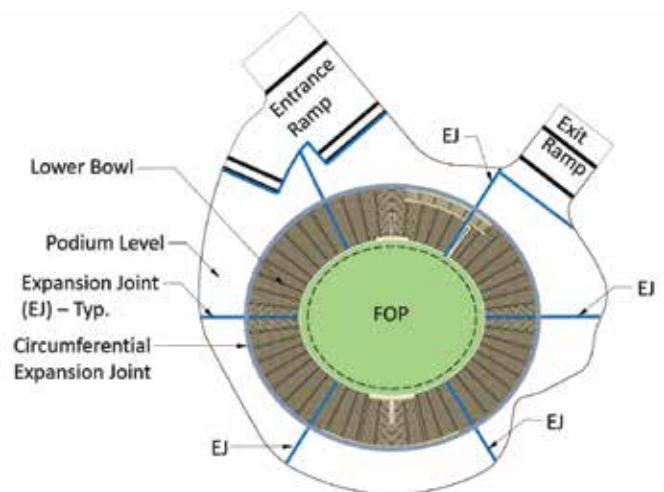


Fig. 1: Lower-bowl and podium-level plan. Radial expansion joints (EJs) break the bowl and podium into six segments, a circumferential expansion joint separates the bowl from the podium, and additional expansion joints separate the ramps from the podium

The structural system for the typical upper-bowl portal frame after discretization comprises Y-columns located on circumferential grids G and H (GY and HY columns), spaced apart and connected with a radial beam at the top (the primary radial beams are labeled PRB 1A and PRB 1B), as shown in Fig. 2 and 3. Five precast circumferential beams connect adjacent portal frames. Due to the large spans between the two primary radial beams, secondary radial beams (SRB) were

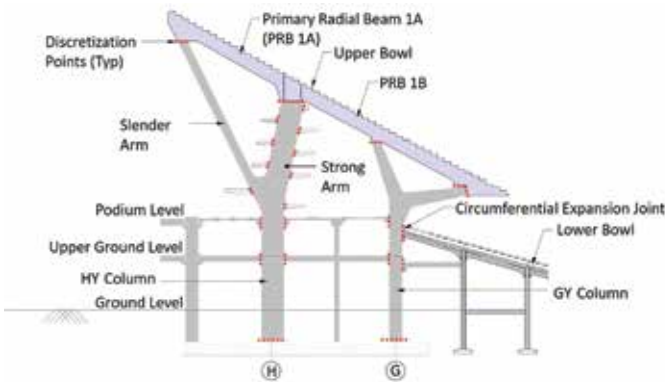


Fig. 2: A typical radial section showing the stadium structure and discretization points on the HY and GY columns

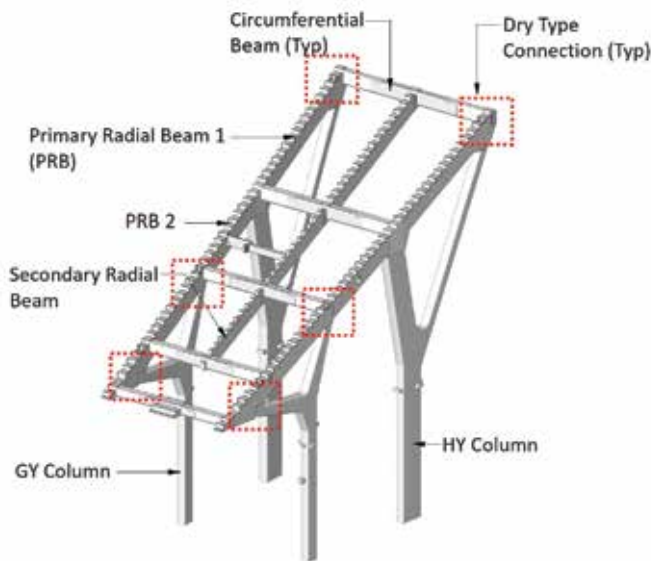


Fig. 3: Three-dimensional view of a typical bay in the upper bowl



Fig. 4: Rendered 3-D computer model of the stadium

introduced to reduce the span of the seating units (Fig. 3). The podium level comprises precast radial and circumferential beams with precast hollow-core slab panels. The upper ground level comprises cast-in-place slab and beams supported on cast-in-place columns. Figure 4 shows an overall three-dimensional (3-D) model of the stadium complex without its roof.

The stadium has a structural steel roof comprising fully locked radial cables connected to an inner tension ring cable and an outer compression ring structure. The structure is covered with a membrane consisting of a woven fiberglass fabric coated with polytetrafluoroethylene (PTFE) stretched between the tension ring and the compression ring. The compression ring comprises top and bottom chord members connected with web elements and supported by V-shaped columns, all fabricated from steel tubes (Fig. 5). The steel roof structure is separated from the concrete bowl structure with an isolation joint all around the column. The forces from the steel structure are transferred to concrete columns at the podium level.

## Design Loads

The gravity loads (dead and live loads) acting on the seating units are calculated and applied as equivalent uniformly distributed loads (UDLs) on the upper- and lower-bowl beams. The wind loads are calculated and applied as UDLs in the upper- and lower-bowl beams, exposed faces of the columns, and at the podium and upper-ground-floor levels. The seating elements are detailed to allow thermal expansion and contraction by movement joints at the end of each element. The loads were calculated per relevant Indian standard codes IS 875 (Part 1) – 1987,<sup>1</sup> IS 875 (Part 2) – 1987,<sup>2</sup> and IS 875 (Part 3) – 2015.<sup>3</sup> The structure is in Seismic Zone-III per the Indian Code IS 1893 – 2002,<sup>4</sup> and dynamic analysis was performed as per provisions available in IS 1893 – 2002.

## Design Life and Durability Criteria

The design life of the stadium is considered 100 years. The durability parameters—namely, concrete grade, reinforcement cover, water-cement ratio ( $w/c$ ), and minimum cement content—were adopted per British standard BS 8500-1:2006 + A1:2012 based on the relevant environmental exposure conditions.<sup>5</sup>

This article is focused on presenting the methods adopted for the design of the large-scale precast elements that form the

structural system of the upper bowl of the stadium. The major precast elements—such as the HY and GY columns, the vomitory staircases around the HY column, the primary radial beam, the secondary beams, and the circumferential beams—are explained herein.

## HY and GY Columns

The HY and GY columns (Fig. 2 and 3) are asymmetrically shaped elements defined by aesthetic and



Fig. 5: Rendered view of roof structure above podium level

functional requirements. Each column is a single joint-free element with a connection to the foundation at the bottom and connections to the radial beam at the top of twin arms. The inclination of each arm was based on the optimum forces at beam-column joints and deflection criteria for the beams. Figure 6 shows the sizes and weights of the HY and GY columns.

### Why a single piece?

Due to the columns' asymmetrical shape—with a strong base and slender arms—casting multiple smaller pieces of different shapes might have been an easier solution than casting each as a single element. However, erecting these elements in alignment and subsequently connecting multiple pieces at height and with limited tolerances would be a herculean task. Hence, it was proposed to cast each entire column as a single piece.

### Design processes and constraints

The columns are vertical elements designed for axial forces, biaxial moments, and shear forces. The forces were determined by modeling the structures between radial joints. Members included Y columns in the vertical position, along with primary and secondary radial beams and circumferential beams at the upper-bowl level; radial and circumferential beams at the podium level; and radial and circumferential beams at the upper ground level (Fig. 2 and 3). The beams were designed to provide the necessary lateral support to the column during service (after all the joints were connected, ensuring fixity). However, both the HY and GY columns were also subjected to major forces during various erection stages. The following stages are explained for the HY column, which is the most critically loaded of the column types.

### Lifting stage

In this stage, the HY column element (which had not yet achieved its full specified strength) was lifted out of the

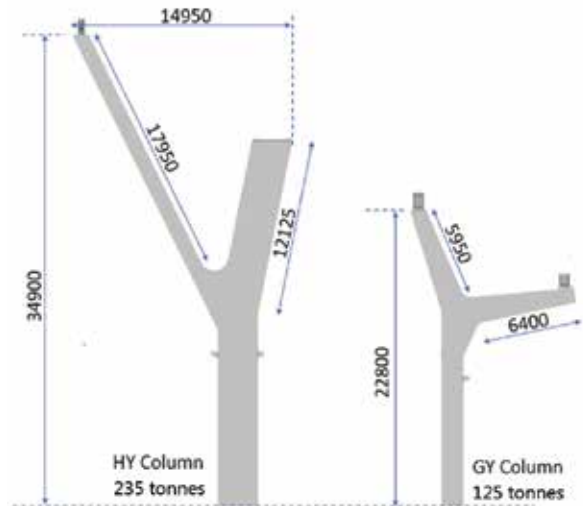
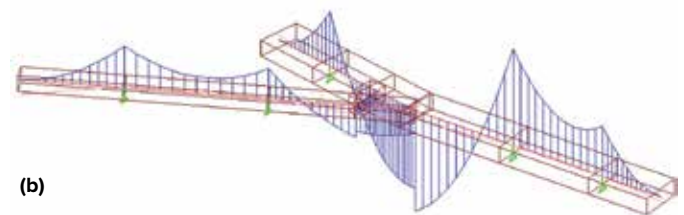


Fig. 6: Dimensions (in mm) and masses (in tonnes) of the HY and GY column units (Note: 1 mm = 0.04 in.; 1 tonne = 2205 lbf)



(a)



(b)

Fig. 7: The very large precast HY column units required special handling: (a) unit being lifted from stacking yard and placed over trailers for transportation; and (b) FEA model showing bending moment diagrams during lifting stage

casting bed and moved to the storage yard (Fig. 7(a)). The lifting points on the element were carefully selected such that stresses were within the permissible limits. An image of the finite element analysis (FEA) model used for analysis is provided in Fig. 7(b).



**Fig. 8:** A precast column is transported to the erection point using trailers. The long, slender legs of precast column units required strongbacks and braces for erection



**Fig. 9:** An HY column is lifted by two cranes

### Transporting stage

In this stage, the precast element was transported using a pair of self-propelled trailers from the storage yard to the location where it would be erected in the stadium (Fig. 8). As the execution site elevations were not uniform, the trailers included hydraulic lifts that were used to avoid imposing major differential movements across the trailer base supports. The structural analysis included these support conditions, and the model was checked for strength and serviceability criteria.

### Erection stage

This was the most critical stage for each HY column. A bespoke C-shaped clamp assembly was used to rotate the element from the horizontal to the vertical position. This clamp was fixed just above the center of gravity (CG) of the precast element, as this allowed the element to be rotated easily with minimal push and guidance. Each HY column was simultaneously lifted by two cranes—one crane connected to the C-shaped clamp and a secondary crane connected to the bottom of the element for guidance (Fig. 9). During the lift, the secondary crane slowly released the load to enable the rotation of the element from the horizontal to the vertical position.

It was essential to ensure that the slender arm, which is 18 m (59 ft) in length, met strength and serviceability criteria. As the slender arm had insufficient section to act as a cantilever, a



**Fig. 10:** A view of an HY column after erection. During rotation, the column was reinforced with a truss tie between the two arms and a strongback extending along the slender arm

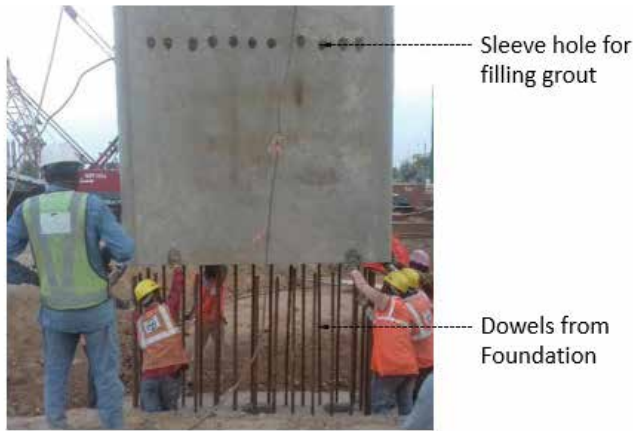
temporary strongback, comprising a fabricated structural steel beam, was connected to the slender arm using bolts. The strongback was removed after the column had been tilted to the vertical position. The analysis was carried out using an FEA model representing the slender arm and strongback as a single element with equivalent stiffness, considering the concrete and structural steel elements as a composite structure.

The slender arm also lacked adequate capacity to act as pure cantilever after the column had been tilted to the vertical position. Hence, a temporary tie, consisting of a structural steel truss, was provided to connect the strong arm and slender arm to control deflection at the free end and cracks at the joint with the vertical portion of the column (Fig. 10). The temporary tie was removed after the primary radial beam had been placed and connected on the top of the HY element.

### Post-erection stage

Upon tilting to the vertical position, the column element was positioned over the foundation. The column was connected to the foundation using corrugated sleeves that were cast in the column and dowel bars that extended from the column foundation (Fig. 11). The corrugated sleeves in the precast element were positioned over the dowel bars, the column was lowered up to the foundation, and the sleeves were grouted. The grout material was a high-strength grout designed to attain the required strength in less than 24 hours, thereby minimizing the crane handling time.

After the grout at the connection achieved the design strength and a temporary lateral steel truss tie had been connected to the column, the crane support was removed from the column elements. The lateral trusses were provided in both radial and circumferential directions at the intermediate levels, and they connected to adjacent HY and GY columns (which were erected sequentially). The trusses were necessary because the column structure was not capable of cantilevering



**Fig. 11: An HY column is lowered over foundation dowels**

35 m (115 ft) above the foundation. After precast beams were connected to the columns in both directions at the top and intermediate levels, the portal action was achieved, and the temporary trusses were removed.

### Primary Radial Beam

The GY and HY columns support primary radial beams (PRBs) in the upper bowl (Fig. 2 and 3). The beam-column joints are laterally supported by circumferential beams. Force transfer from the radial beam to the column is achieved by structural steel elements embedded in and extending from the HY and GY columns into pockets formed in the bottoms of the radial beams (Fig. 12). The pockets were sized to provide for erection tolerances and to provide space for grout to flow around the structural steel after erection.

PRB elements were transported to the jobsite on trailers, with support points selected to minimize stresses on the beams. At the jobsite, the beams were rotated to the required angle using bespoke spreader beams, lifted to position the pockets over the structural steel elements in the columns, and carefully lowered until the steel elements were completely embedded in their respective pockets. The beam elements were held by the crane until the pockets had been filled with high-strength grout and the grout had achieved sufficient strength.

### Circumferential Beam

The center portions of the circumferential beams were precast concrete with dowel bars extending from both ends. Cast-in-place concrete was used to fill the portion of the circumferential beam between the precast part of the circumferential beam and the PRB. This was achieved by placing the center portions of circumferential beam elements inside specially fabricated steel cages along with necessary materials and machinery, lifting the assembly by crane, and placing the assembly over the PRB elements (Fig. 13). Couplers were used to connect the threaded dowels in the PRB elements with additional reinforcing bars that were lapped with the dowels of the circumferential beam elements. Shear reinforcement was then tied in place, and formwork was



**Fig. 12: The columns were produced with structural steel embedments at upper connection points: (a) embedments extending from column end; (b) corresponding pockets in bottom of PRB; and (c) a completed connection of a column end to a PRB**

assembled around the resulting reinforcing bar cage. This procedure eliminated the need for scaffolding and allowed workers to place concrete 35 m (115 ft) above the street level. After the cast-in-place concrete had achieved adequate strength, the steel cage for each circumferential beam element was removed.

### Secondary radial beam

After all the circumferential beam elements were placed and the joint concrete was cast, secondary radial beams (SRBs)



**Fig. 13: A precast concrete circumferential beam is lifted into place. The beam is enclosed in a bespoke truss assembly to allow safe completion of cast-in-place connections to the radial frames**

were placed over corbels provided in the circumferential beam elements. Both circumferential beam and SRB elements were provided with sleeves, and steel rods were inserted in the sleeves and grouted to resist lateral shear forces (Fig. 14).

After all the grouted and cast-in-place concrete joints had reached their design strengths and SRB elements were erected, the entire portal structure was complete. Then double L-shaped stadia elements were lifted into place between the PRB and SRB elements to complete the upper bowl.

### Vomitory staircases

Spectators reach the upper bowl via vomitory staircases. The stairs cantilever from the HY column, creating an aesthetically pleasing but complicated staircase consisting of precast and structural steel. The stair landing consists of a precast slab supported by cantilevered steel beams. The stair slabs are precast concrete supported on the landing slab and cantilevered steel beams. The inserts for fixing the steel beams to the HY columns were embedded in the column at predefined locations during casting. Figure 15 illustrates the completed staircases.

### Conclusion

Even though precast design and construction is not a new technology, adopting precast for complex, large-scale elements is not an easy task. Motera Stadium's structure required microlevel design verification, planning, and monitoring during each stage of construction. While large-scale elements minimize the number of elements and joints, handling the individual elements during various stages must



(a)



(b)

**Fig. 14: Secondary radial beams (SRBs) were supported on circumferential beams: (a) view of a lower secondary beam; and (b) view of a completed bay**



**Fig. 15: Vomitory staircases at HY columns**

be critically analyzed and the elements must be designed accordingly. The world's largest cricket stadium is a complete success in terms of adopting large-scale precast elements by using innovative design, detailing, and erection techniques. This experience has provided us with the confidence to adopt large-scale precast elements of any shape in future.

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Selected for reader interest by the editors.



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