Surveying the Moses Mabhida Stadium

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As with most construction projects, architectural marvels pose a number of challenges in the construction phase with a large number of these often being survey challenges. Durban’s new Moses Mabhida Stadium is no different.

Built to host soccer matches for the 2010 FIFA World Cup, the stadium is located on the grounds of the Kings Park Soccer Stadium in Durban. The stadium has the capacity to hold 70 000 spectators during World Cup soccer matches, and its design allows the seating to be reduced to 54 000 for local matches or up-scaled to 80 000 for major international events. It has two permanent tiers of seating, with a temporary third one having been added for the World Cup [1].

A 350 m long and 105 m high span arch holds up the roof of the stadium, with the top of the arch rising to 106 m above the pitch. The arch consists of a 5 x 5 m steel hollow box and weighs 2600 tonnes. A cable railway carries visitors from the north side of the stadium to a viewing platform at the top of the arch, offering a view over the city and the Indian Ocean [1].

The stadium’s roof, which covers 88% of the seats, consists of a 46 000 m², Teflon-coated, glass-fibre membrane which is attached to the arch by 95 mm diameter steel cables. Around the perimeter, the different levels of the stadium are supported by 1750 columns and 216 raking beams that provide the main support to the seating panels [2]. A total of 1780 pre-cast concrete seating panels create the bowl form and over 100 columns of varying height comprise the façade of the stadium, with the highest being 46 m [1].

Survey team

The survey team on site was made up as follows:

- The main contractor was a joint venture between PBC and VP Surveys with Vaughan Perkins, Rick Rosa and Bruce Hopkins, all registered surveyors with PLATO, being responsible for most of the surveying. Other surveyors assisted with control and setting out as needed. This team was responsible for all concrete setting out of the main structure from pile caps to the 6th floor slab.
- The consultants on the job, ILC, were responsible for the main
concrete structure with Craig Silva of Align Survey (also PLATO registered) performing checks on the contractor for quality assurance purposes.

- The roof structure contractor was German company Pfeifer and Craig Silva of Align Survey was responsible for all setting out and checking of the roof structure.

**Survey control system**

The survey control system was made up of eight primary pillar beacons with forced centering plates cast in. The initial fix on the beacons was done as a network based on the local TSM network. Secondary control was placed from this primary network and was made up of both concreted pegs as well as Leica Retro Targets.

Benchmarks were disturbed and destroyed weekly by the contractor. As a quality control check all benchmarks were checked at least once a month and new benchmarks were placed where new works started or old benchmarks were obstructed. These results were submitted to the consulting team for checks and approval.

**Main concrete structure**

The main structure survey department was run by VP Surveys and Vaughan Perkins and Rick Rosa were on site for most of the construction period dealing with the demanding survey issues. One of the main challenges to face them was the erection of the outer columns of the main structure which would hold the compression ring for the roof.

These giant columns, 50 to 60 tons in weight, were precast (see Fig. 1) and raised by a Mammoet crane into position (see Fig. 2) where, after alignment, the columns were braced for grouting. This was no easy task as the top of the columns were 24 m high and the surveyors had to deal with the steep angles as well as the busy construction site which made setting up the instrument to site the top targets extremely difficult.

Leica TPS1200 total stations were used for the positioning and alignment of the columns. Leica Retro Targets were placed on the top corners of the column and were used to monitor and adjust the beam (see Figs. 4 and 5). Each of the 102 columns was designed at a different rake and the large cast in plate on the top, which would accommodate the steel lug to hold...
initially the scope of work did not include the extraction of data for construction fabrication of the necessary models. The scope of work was later amended to include the extraction of data. The beam design drawings were already published for use in the construction. We produced comparison drawings indicating the actual as-built dimensions and differences to aid the fabrication process in providing more accurate fabrication parameters.

the roof structure, had to be adjusted vertically to the correct level. As the columns formed part of the upper floor slabs which were not cast as yet, all measurements had to be taken from ground level. There was no possibility of adjustment after grouting, and once the crane had unhooked, checks had to be made to ensure the columns were braced in the correct position.

The second challenging item of the main structure was the placing and level control of the cast in situ raked beams to hold the precast seats (see Fig. 3). All the seating were individually cast and placed on raked columns with tight tolerances. Each step had to be checked pre- and post-concrete to ensure a perfect fit when the precast panels arrived.

**Column as-builts and façade beam details using 3D laser scanning**

Between the concrete precast columns, a façade had to be designed for the outside of the building. This consisted of horizontal beams that vertical "fins" would be attached to. An as-built survey was necessary to calculate the exact dimensions between the concrete columns. Due to the difficulty with getting access to the exact connecting position of the beam between the columns, we suggested scanning the surface and building a model from which the measurements could be taken. Brad Inggs from Precision Engineering Geomatics (PEG) did the scanning of these outer columns (see Fig. 6).

The design of Moses Mabhida Stadium uses 102 columns. At base level these columns occupy an oval shape. To help increase spectator seating capacity, the columns on the "long side of the playing field" rake outwards to form a more circular arrangement as they climb toward the compression ring.

If you divide the design into four mirrored sectors, each adjacent column has a different raking angle and different sector angle to its adjacent neighbours. Each unique column structure is repeated four times within the total circumference. There are two columns missing at the south end where an entrance is provided beneath the great arch for "march-ons, large vehicles etc."

The façades are an arrangement of vertically oriented "fins" that provide aesthetic appeal to the overall appearance of the stadium. These façades are supported by two beams between each column and it was the accurate fabrication and fitting of each unique beam that provided the challenge and opportunity to utilise 3D laser scanning (see Fig. 7).

The scope of work required an as-built 3D model of all columns in AutoCAD format including a horizontal section every 1 m vertically and 5 horizontal sections 200 mm apart at each beam tie-in zone. The surveyors on site realised that 3D laser scanning technology provided the best solution to creating accurate as-built data of the stadium columns as the acquisition of such data with a reflectorless total station would not meet the tight turnaround schedule for the deliverable data.

A Leica HDS3000 time-of-flight laser scanner was used to scan the columns...
in fine detail (10 x 10 mm) and the outer precinct of the stadium in lesser detail. The columns were scanned from 14 set-up points in two and a half days by a two-man team. While the scanner operator was busy, the second surveyor chose the optimal positions for scan control points and fixed these points with a total station from the stadium coordinate grid. This site was extremely busy with personnel, cranes, vehicles and scaffolding unavoidably obscuring the line-of-sight. Scaffolding provided the biggest challenge as it could not be removed. Fortunately we were able to scan at a high density in these areas and obtain sufficient data to accurately model the surfaces comprising the columns, even though the data had a checkered look from the shadows created by the scaffolding members (see Fig. 8).

Tying the 3D entity into the stadium grid was a seamless exercise as the stadium has excellent survey control surrounding the entire structure and this control is monitored weekly. The mean absolute error for the registration of all 14 scans onto the stadium control was within 5 mm. However, some deviations within the final misclosures were experienced while on site. The Leica HDS3000 weighs 22 kg and the supporting tripod can experience some settlement during long set-ups when not on hard-stand surfaces. The integrity of the scan data was constantly verified by re-acquiring all target positions during and at the end of a set-up before moving. Two set-ups were repeated because of this tripod settlement.

The roof structure

The roof structure comprises three main elements. The arch, the compression ring and the cable net (comprising of radial cables and an inner cable ring). The design can simply be equated to a bicycle wheel where the compression ring is the outer rim of the wheel, the cable ring is the inner hub and the cables are the spokes. The arch is above all of these and helps suspend the cable network. All the components when connected to each other form the full roof structure. Without any one of these components, the others would not stay erected as they all hold each other up.

The arch

The arch was comprised of 56 elements all bolted together. Each element had eight survey reference points punched into the arch at the factory after
manufacture. These were placed a set distance from the machined face. These points were used to survey and geometrically fit and adjust the arch. These positions then had retro targets placed on them for the measurement (see Fig. 9).

The design of the arch allowed for a manufacturing error of 10 mm on each arch element, however, if all the error was in the same direction, the arch would not fit on its preset bases. A trial assembly was done in the factory yard before the pieces were shipped from Hamburg, Germany.

**Trial assembly procedure**

Eight pieces were bolted together and jacked up to be in a situation of no tension. The reference points were measured with a total station on a local system and the results sent to site. Only six of the elements were then transported to Durban while the next six were made. The process was repeated using the common two elements from the first trial assembly to measure the next set of elements. This procedure was repeated until all the elements were built.

These results were transformed and compared to the design model and a best fit was achieved. As the manufacturing errors that occur are often in the same direction, the next element being built was adjusted to compensate for the error.

A similar process occurred on site. The points had to be measured at night as the sun had 100% effect on the steel structure. At 40% complete, the sun would cause heating on the east side in the morning and cause the arch to expand on the one side and go out of alignment by 20 to 30 mm. The same would happen in the afternoon as the sun heated up the structure on the west side.

Measurement would take place from 00h00 to 04h00 in the morning. A Leica TPS1200 was used for these measurements. Due to the night measurements, automatic target recognition (ATR) was important as prisms on control beacons could not be seen clearly. The side of the arch was floodlit to see the retro targets’ places on the punch marks on the arch. These results were compared to the design, and adjustments were made using hydraulic jacking systems to move the elements.

Each erection stage had a unique set of coordinated points to define the arch geometry. The position of the arch could not be placed in the final position from the start as gravity and the weight of the next elements influenced each installation. Each stage was known as a load case and a unique set of co-ordinates were calculated for each segment at each erection stage. This was done to ensure the installation was done with the least amount of stress on the structure.

Before placing an element, the arch in its current stage was lifted to a pre-installation position and then, after another element was installed, re-measured to check that all design criteria were achieved. The position, weight and tension on the hydraulic jacks holding the arch in place were all interlinked – as the arch moved down under the new weight so the hydraulic jacks’ tension increased. This overlapping allowed for cross checks on the survey as well as the safety of the erection.
Placing of the last piece

To place the last piece, either side of the arch had to be hydraulically jacked apart 20 mm to allow for 10 mm either side for the last piece to be slotted in. As the piece fitted between the two elements, the hydraulic jacks were simultaneously released to close against the last piece. The rate at which the hydraulic jacks were released was controlled by survey on the front two targets until the gap was closed (see Figs. 12, 13, and 14).

Compression ring

The compression ring was constructed using the same procedure as the arch. The compression ring would sit on top of a steel column connected to the top of the precast columns by means of a steel lug welded to the cast in plate on the concrete columns.

However an added error that could occur during manufacture was in the steel facade column and this had to be catered for. Although in tolerance, the error in height could place a vertical stress on the compression ring. All the errors from the trial assembly were assessed and the steel lug that would be attached to the cast in plate on site was adjusted to compensate for the accumulative manufacturing error.

The columns were measured and adjusted by means of a temporary push-pull system attached to the columns. This also adjusted the compression ring once placed onto the steel columns. Once again measurements were done at night and adjustments made first thing in the morning. This was repeated every night during assembly.

Cable net

The cable net is a network of cables that holds the roof sheeting/membrane. This consists of cables which link the compression ring to the arch and suspends an inner cable ring made up of six cables. This network of cables was laid out on the ground and connected to the compression ring before being jacked up using hydraulic jacks to connect to the arch (see Fig. 15).

Each connection point had a steel cast item connecting the cables. Each of these positions had to be carefully monitored during the lift to ensure the cable net was lifted horizontally (within design criteria) and that none had been installed out of position. Retro targets were also placed on each cast item, measured at night and compared to design. The design position for each item was determined by the pressure on the hydraulic jacks. Each of the 102 hydraulic jacks’ pressure was measured and then the design position calculated for the current position.

This measurement was taken every 10 m that the net was vertically lifted until connection with the arch. Once again measurement was done at night using a Leica TPS1200 as the heat caused the cables to lengthen. About 600 target positions had to be measured and the centre of the element, which was the system point (setting out point) needed to be calculated for comparison.

Final survey

Once the full structure had been assembled and all cables joined – a full survey of all items was done to ensure that the roof structure was within tolerances. This survey could also be used for future measurement comparisons if necessary. During the final measurement approximately 2500 points were measured during the night for the final as-built comparison.

Conclusion

With such unique architectural and engineering designs being built in South Africa for the World Cup, our engineering and construction sector has proven itself to be capable of undertaking such challenges and completing them to a high standard. Surveyors have always played an important role as part of the engineering team, from start to finish, and Durban’s Moses Mabhida Stadium is evidence of the high quality work that South African surveyors are able to produce.

References


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