Challenges of Stadium Construction—Case Study
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Abstract: The distinctive design and construction requirements of an outdoor athletic stadium in Haifa, Israel, are described in this paper. This open-air stadium accommodates approximately 2,400 seats in its upper deck, while the lower part of the stadium contains offices and visitors’ facilities. The stadium has a distinctive arrangement of 30 m high bowed-concrete columns from which 24 m long curved concrete beams are cantilevered. Because of restricted access to the project site, it was necessary to cast the stadium’s concrete columns and beams on site and then lift these elements with large cranes.

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Introduction

The construction of a sports stadium always involves a complex arrangement of structural components. Moreover, as the structural components must bridge considerable spans they tend to be massive, heavy, and difficult to handle such as those in the Millennium Stadium in Cardiff, United Kingdom (Corus Construction Centre 2004) and Miller Park Stadium in Milwaukee, Wis. The challenges and risk of constructing these structures and of handling the large structural components were amply illustrated when the crane lifting a 450 t load at the Miller Park Stadium collapsed in 1999 dropping a large section of preassembled roof truss (Schexnayder 2003). The results were three fatalities, five other workers injured, and more than $100 million in project damage. The vibration caused by the crane’s collapse was severe enough to be measured on the seismograph at the Univ. of Wisconsin-Milwaukee, Wis.

Many stadiums built since the mid-1980s have had large cast-in-place concrete components. The Toronto multipurpose stadium—The SkyDome—is an example of such work (Hurd 1990). The casting of the concrete components for the SkyDome was accomplished using special metal forms, designed specially for the project and this has been true for many other stadium projects (Shald and Gottlob 1994).

This paper describes the distinctive design and the construction methods used to build an open-air athletic stadium in Haifa, Israel. While not as large or as complex an undertaking as either the SkyDome or the Miller Park Stadium the construction of the Haifa stadium had its own unique construction challenges. The stadium is located in the northern section of the city. A previous stadium existed at this site since 1992; however, with time it was found to lack the necessary space required to accommodate the large number of visitors coming to the various athletic competitions. Therefore, Haifa’s municipal Division of Sports, Culture, and Arts decided to construct a new 32,000 m² stadium, with increased capacity and better facilities to serve both the event attendees and the competing teams.

Stadium Design

The stadium’s superstructure has two major parts: (1) an upper part containing the seating area for spectators; and (2) a lower part containing offices, visitors’ facilities, restaurants, dressing rooms for teams and officials, a gymnasium, and storerooms. Fig. 1 presents a view of the confined construction area and the edge of the athletic field at the beginning of construction. The new stadium is squeezed between the pre-existing track and field area, the campus of the Technion–Israel Institute of Technology to its rear, and the tennis courts of a private club. The area with trees and multistory dormitories in the upper part of Fig. 1 is the campus of the Technion.

The city of Haifa, as well as the architect and the structural designer, wanted the stadium to be an impressive structure, an architectural achievement, and a model for other sport stadiums. The result of this desire was a design having 30 m high bow-shaped concrete columns from which 24 m long curved concrete beams are cantilevered. These concrete beams will provide the support for a roof canopy to shelter the seating area. In addition, there are five arched steel beams that tie adjacent columns together and serve to maintain column spacing. Similar arched steel beams at the extended end of the cantilevered concrete beams tie the adjacent concrete beams together and serve to maintain their spacing.
The canopy roof will be hung from these arched steel beams. The steel beams are arched for the purpose of giving the canopy roof the desired aesthetic effect. There is also a 10 m high rear concrete wall connecting the foundation with the second floor (upper part) of the stands. The cost of the structural phase, the work described here, was $2.1 million.

Unique Features

Three aspects of the stadium construction were unique:

1. **Size of the columns and beams.** The construction company for the project had extensive construction experience, but it had never built such a unique structure. These were some of the largest concrete components ever cast in Israel, particularly the columns and beams.

2. **Bowed concrete columns and curved concrete beams.** Because of their shapes, the concrete columns and beams required special forms. These forming systems were custom designed and built for the project. In addition, all of these large concrete elements were cast at the construction site. This on-site casting requirement necessitated careful planning as to the sequence of construction operations, the selection of lifting equipment, and the positioning of the selected lifting equipment.

3. **Crane requirements.** A Demag CC2000 crawler crane was required to hoist and place the columns in their correct positions on top of their foundation pile caps (Fig. 2). This crane was rented from Avi Cranes Ltd., Israel (Avi 2004); it is capable of hoisting a maximum load of 300 t and has a 4,000 t m moment rating. At the time of the project it was the third largest crane in Israel. In addition, two hydraulic all-terrain mobile cranes, also rented from Avi Cranes, were used on the project. The larger of these two mobile cranes was a seven-axle Liebherr LTM1400, capable of hoisting a 400 t maximum load (or a moment of 1,270 t m). The other was a five-axle Liebherr LTM1200, capable of hoisting a 200 t maximum load (650 t m). In hoisting the concrete structural elements one or both of these hydraulic cranes were often required because of the shape of the elements. Avi Cranes, the supplier of these cranes, is the largest crane rental company in Israel and the Middle East.

Bowed Concrete Columns

The stadium has six 30 m high bowed concrete columns (Fig. 3). The clear spacing between the columns is 8 m. All of these columns have the same geometry, but the foundation pile cap for one column had to be modified because of unforeseen site conditions. The design strength of the concrete for the columns was 70 MPa. The column base dimensions are 471 × 80 cm. The top dimensions are 80 × 80 cm. Each of these columns weighs approximately 150 t.

Israeli design standards do not address such tall concrete elements. Therefore, the columns were designed according to the European standard (EuroCode-2) and the German standard (DIN). The design calculations were checked using a finite elements code that predicted behavior to failure and accounted for earthquake loadings.

Construction Alternatives

Different alternatives were considered for constructing the columns, but their weight and the limited access to the project site prevented casting of a 30 m long column at a fixed off-site facility. The road system up Mount Carmel to the project site is of limited width and has too many tight curves to allow transport of such large and long concrete elements. Therefore, another construction plan had to be developed.

Because the moment generated by the curved shape would have to be restrained by the formwork until the concrete had gained its strength and the column could be tied to its foundation, in-place casting of a full 30 m high column was not practical and that approach was rejected as soon as a preliminary analysis of the forces had been conducted.

Consequently, the contractor’s first proposed solution to the construction problem was to cast the columns in-place in 6 m segments or to precast 6 m segments. When this idea was presented to the structural designer it was immediately rejected. The designer did not want the columns to have four construction joints. The contractor then suggested casting the first 6 m in-place and precasting the upper 24 m. Again the designer turned the proposal down; he demanded a monolithic column—no construction joints would be allowed.
Selected Construction Method

The only remaining solution was to precast the full 30 m column on site. To accomplish this, the contractor had Avidan Metal Industries Ltd. manufacture unique metal forms for the project. The plan was to cast the columns on their backs, concave side to the ground. This means that while the forming system rested on the ground at each end, vertical shoring was required to support the middle part of the column’s concave shape. This construction approach did enhance safety and working efficiency as the work was close to the ground instead of 30 m in the air.

Avidan designed a forming system having truss-like steel supporting towers. The upper surface of each tower was part of the form and the concrete of the column bore directly on this surface. This support requirement resulted from: (1) the fact that the contractor wanted to strip the forms and reuse them without having to wait until the concrete reached its full design strength; and (2) the columns were not designed to support themselves in the horizontal plane while supported only at their two extreme end points. Just below the upper surface of the towers there was a lip to receive a lower form that stretched between the towers for shaping and supporting the underside (actually the back) of the column during casting. While the support towers had to remain in place until the columns were hoisted into position, the underside forms could be removed and reused. Consequently, only one set of forms was required for the six columns; however, six sets of towers were required, one set per column.

Concrete Mix

The design strength of the concrete for both the columns and beams was 70 MPa. There was also a contractor-imposed requirement that a 40 MPa strength be reached in 36 h so that the forms could be stripped and reused rapidly. The on-site casting of the columns and beams took place during the winter months so the ready-mix supplier formulated the mix design based on an expected external temperature of 15°C. Because of this temperature assumption no retarder was used with the high-early strength, rapid-setting cement CEM I 52.5 R (under the European Code EN 197). The use of this rapid-setting cement without a retarder, however, required very close coordination between the batch plant and the casting operation. Trucks arriving at the site had to immediately discharge their concrete into the forms. Additionally, it was required to use a batch plant located very close to the project site; therefore a plant within a 3 km radius was chosen.

The concrete mix was composed of three aggregate types: (1) crushed coarse aggregate, 6–14 mm size range, 45% of the total aggregates by weight; (2) graded crushed fine aggregate, 0–5 mm size range, 30% by weight; and (3) natural sand, 0–1 mm size range, 25% by weight. The cement content was 450 kg/m³. The water–cement ratio of the mix was 0.33 and the mix had a slump of 160 mm. A superplasticizer was also added to make the mix free flowing (workable) and to help alleviate voids.

Another feature of using this type of cement was the development of a curing process specifically for the mix and the project conditions. Special, patented curing sheets manufactured by Tayatex Ltd. of Israel were used to cover the concrete. About 1 h after casting, the sheets were placed over the exposed concrete surface. After stripping the forms the concrete was wetted and the sheets then wrapped around the entire element. The Tayatex’s sheets meet the requirements of ASTM C171, “Standard specification for sheet materials for curing concrete.”
Casting Columns

A Simma 23.48 A10 tower crane traveling on rails, which was on site for this casting work and other stadium concrete work (approximately 12 months), was used to handle the forms, transport reinforcing steel, and place concrete. The rails for this crane were positioned just beyond the front edge of the new stadium’s footprint. This crane also provided lifting capability for the 51/2–6 t precast concrete panels that were erected on the stadium’s cast-in-place concrete work.

One full month was required to accomplish casting of concrete bases for the support towers of all six columns, as well as assembling the forming system for the first time, placement of reinforcing steel in the forms, and casting of the first column. Each column required approximately 20 t of reinforcing steel and 60 m³ of concrete. The primary reinforcing steel in the columns is 25 and 32 mm bars. Production improved after casting the first column and approximately 2 weeks were required to complete each of the other five columns.

As there was no other space and no crane on site capable of lifting them, the completed columns remained on their towers, where they were cast, until they were hoisted into position. The casting and storage location was within the footprint of the stadium and work on that part of the stadium had to be delayed until the columns were erected.

Usually, such concrete elements must be prestressed (D’Arcy et al. 1990) and that was the case with the Haifa stadium. Each column had a system of eight stressing cables. These cables were each post-tensioned to 1,700 kN. The calculated cable loading is 1,400 kN. Three of the cables were for connecting the column to the pile foundation, while the others were arranged to control cracking. Each column also contained utilities—water pipes and ducts for electrical cables. Additionally, mountaineering hooks were placed on the upper face of each column for climbing competitions.

Column Foundations

The foundation design had the two end columns supported by nine drilled and grouted micropiles, and the four inner columns by 11 piles. All of the piles were 45 cm in diameter and 16 m in depth. In plan view, the pile caps for all the columns had a T-shape. The top of the T was to the front of the stadium. The top crossbar of the T had five supporting piles in the case of the two end columns and seven piles for the inner columns. The base of all the T’s was designed to have four piles. The rear (base of the T) piles are in tension because of the overturning moment created by the cantilevered concrete beams. The top surface of the pile caps has a 35 cm deep cavity into which the base of the column is positioned. This socket was included in the design to facilitate positioning of the columns during the erection procedure and to prevent sliding of the column on its base. On each column at a height of 10 m, there is a special receiving base for the curved concrete beams.

Hoisting and Placing Columns

Raising and positioning the columns was an intricate process, since it required lifting and positioning such heavy loads with the added constraint of very limited space for locating the cranes. Additionally, all of the column hoists were dual picks by the 300 t crawler crane and the 400 t all-terrain crane, as shown in Fig. 4. Under the ASCE Manual of Practice No. 93 guidance (Burkart 1998), all of these lifts would be classified as critical lifts requiring a critical lift plan. Similar to what the manual recommends, the projected travel path of load hoisting and swing from liftoff until final placement was plotted for each lift. Fig. 5 is the travel path plans for lifting the second column (an end column).

Fig. 4. Using Demag CC2000 (crawler in rear) and Liebherr LTM1400 (all-terrain in front) to lift concrete column

Fig. 2 shows the first column being hoisted into position at the stadium. The two end columns were placed first, then the four central columns. This was done because of the site constraints—the confined project site forced the casting of the columns in the center of the site. The hoisting and positioning operation for all six columns took 4 days.

At the beginning of the pick the column is in a horizontal position as it is hoisted off the shoring towers (Fig. 5, Step 1). A hole was cast into the column to receive the lifting pin that connected to the slings of the crawler crane. This sling and pin connection can be seen in Fig. 4. The plan was for the 400 t all-terrain crane to always carry 40 t of load during this portion of the hoist. The operator of the all-terrain crane monitored this on the readout of his load device. Once a column was raised and swung clear of the storage/casting area, the crawler crane began to lift and the all-terrain held the butt of the column above the ground until the piece was rotated into the vertical position (Fig. 5, Step 2). Once the rotation was completed the all-terrain crane released its line and its sling swung clear. From that point on column positioning was accomplished by the crawler crane alone (Fig. 5, Steps 3 and 4). With each column this was a little different because of their respective locations but the sequence was: (1) lift above the storage/casting area; (2) swing clear of the storage/casting area and bring the column to the vertical; (3) swing to a carrying position; (4) walk the crane to the pile cap location; and (5) position the column on its base. As the columns are on the back side of the stadium and the storage area was on the front side all of the columns had to be moved 180°, but because of the crane being positioned between these two locations the amount of crane swing was typically on the order of 120°.

One day was required to assemble the large crawler crane on site and an additional day was required for dismantling. Positioning the first column proved very difficult and required 1 full day, while the five other columns were set in 1/2 day each.
Curved Concrete Beams

Each of the six columns supports a curved concrete beam that cantilevers over the seating area of the stadium. These beams have a horizontal length of 24 m and each weighs 37 t. As with the columns, the beams were cast at the project site. The formwork for casting the beams was similar to that for the columns. Custom truss-like steel supporting towers were used so that during casting, the beam was positioned in the same axes as when it was later erected in the structure. This had to be done because that was the only axis for which they were designed to carry a load and because of their concaved shape, temporary shoring was necessary to support the middle of the curve during casting and storage. The special metal forms for site casting these beams were custom manufactured by Avidan Metal Industries. Fig. 6 shows the finished beams stored on their custom shoring towers at the project site.

Ten days were required to cast the first beam. This duration included the assembly of the metal forms, installation of reinforcing steel, and the placement of the concrete. In each beam there are 4 to 6 reinforcing steel, in bar sizes of 25 and 32 mm. The volume of concrete in each beam is approximately 13.5 m$^3$. Each of the other five beams required 1 week to complete. The concrete mixture used for the beams was the same as used in constructing the columns, therefore the metal forms could be removed after only 24 h of curing.

Four 40 mm diameter prestressing cables were installed at the base of each beam for tying it to its column. At the location on the column where the beams were seated, sleeves were cast into the columns to receive these cables: an individual sleeve for each cable. Since these special cables could not be found in Israel, they were procured from the United Kingdom. After completion of the roof work, each cable will deliver 70% of its maximum rated stress. The calculated loading is 400 kN. Fig. 7 presents the concrete beam drawing.

Tendons

Steel hold-back tendons were used to tie the outer end of each concrete beam back to the top of its supporting column. These 50 mm diameter tendons were also imported from the United Kingdom. Each of these tendons is capable of holding a 1,000 kN load.

Besides the hold-back tendon, there are cross bracing tendons connected to the cantilevered beams at a point approximately 8 m from their outer end; a plan view of the attachment point can be seen in Fig. 7. Each interior beam has two of these cross bracing tendons. The exterior beams have only one cross bracing tendon.
These tendons run back to adjacent columns and connect to the face of the columns at a point approximately 2 m above the uppermost point of the column’s beam receiving base. The combination of tendons from adjoining beams creates an “X” pattern.

**Hoisting and Placing Beams**

It took 5 months to complete all of the column stabilizing work, post-tensioning to the foundation cap, and casting of the connecting rear stadium wall. Once that work was completed the concrete beams were raised from the storage site and attached to the columns. There was a special receiving base cast into each column (Fig. 3). The erection of these beams was a dual hoist by the two all-terrain cranes. This dual pick requirement was caused by the curved shape of the beam. In fact these lifts were much more complex than the column lifts. Consequently, critical lift plans were prepared similar to those used for lifting the columns with the projected travel path of hoisting and swinging the beams from liftoff until final placement being plotted for each beam lift.

While the beams were not nearly as heavy as the columns, so load weight was not as critical an issue, there was the added consideration when lifting the beams that they had to be connected to the columns before the crane could release the load.
Connecting a beam to its column involved threading in the prestressing cables at the column, as well as attaching and tensioning the hold-back tendons. To accomplish lifting and holding the 50 mm hold-back tendons, while they were being connected to the tops of the columns, it was necessary to use the tower crane or the second all-terrain crane depending on which beam was being placed. The second all-terrain crane could not be positioned to reach the hold-back tendons of those beams that cantilevered over that section of the stadium that had already been constructed (Fig. 8). However, once the beam placement operation reached the area where the stadium seating area had not yet been constructed, the second all-terrain crane was used to handle the hold-back tendons (Fig. 9). The workmen who were engaged in connecting the tendon to the column used a manlift (aerial platform) positioned on the backside of the stadium to reach the top of the columns. The manlift can be seen in the lower right of Fig. 8 and in Fig. 9.

Additionally, temporary spreader braces had to be set in place about 8 m from the outer ends of the beams to keep them correctly positioned until the permanent steel beams were installed. The only way to get workmen to that location on the beams while the all-terrain cranes were positioned for lifting beams was the use of a man basket lifted by the tower crane (Fig. 10). The use of a man basket handled by a tower crane requires a special permit, as regulation No. 65 of the Israeli Work Safety regulations (1994) specifically states, “A tower crane shall not be used to lift people.” A certified inspector indeed examined the man basket that was used on this project.

Temporary cables were used during the erection work in place of the cross bracing tendons. The cross bracing tendons were placed later and the beam spacing adjusted at that time.

At the beam’s butt end, the upper flange extends out and fits over the receiving base on the column. This over-flange extension can be seen in Figs. 7 and 8. To properly set the beam on the receiving base of the column, it is necessary to approach the base with the outer end of the beam tilted down. This ensures that the web part of the beam comes into contact with the receiving base first and the flange extension is not damaged during the setting process. After the web has made contact, the beam must be rotated in the vertical plane so that the flange fits securely on the receiving base. To accomplish this maneuver, while the beam is suspended by the slings, two hydraulic cylinders were incorporated into the section of the sling holding the outer end of the beam. In Fig. 8 these cylinders can be seen in the left part of the sling. The hydraulic cylinders were connected to ground-mounted pumps and the operation of the cylinders was controlled from the ground. The pistons of these cylinders were extended during the raising of the beam. Then when the flange of the beam was in contact with the receiving base on the column, the beam was rotated into its final position by retracting the pistons—shorting the outer sling. The erection of the beams onto their columns, together with the connection of all beam tendons, took 1 week.

Steel Beams

Further structural stiffening of the concrete columns and their beams is provided by concaved steel beams that tie adjacent columns and adjacent beams together. These steel beams, weighing 2.5 t each, will serve as the structural element to which the roof canopy will be attached in a later contract. The rear steel beams connect to the columns at the point where the concrete beams connect to the columns, as shown in Fig. 11; the front steel beams are attached to the cantilevered concrete beams at their outer ends. Each steel beam is actually a paired element forming an envelope that was filled with concrete so that they act as counter-weights to the aerodynamic effects of roof loadings.
Concrete Walls

The design strength for all of the cast-in-place stadium concrete was the same as for all the precast elements, 70 MPa. Rear and side walls serve to stiffen the stadium and particularly the columns as they rise from their pile foundations. These cast-in-place walls have a thickness of 20 cm. The rear wall has a height of 10 m. The side walls taper down with the sloped seating of the stadium.

Other Construction Challenges

The constructor of this project had to overcome three major challenges.

Unforeseen Site Conditions

Prior to construction there was only a very limited investigation of the project site. As a result, during construction of the drilled and grouted micropiles for the column No. 1 foundation, a 1.80 m diameter drainage pipe was discovered within the area that the rear piles of the T-shaped pile cap were supposed to occupy. The depth of this drainage pipe was 2 m below the ground surface. This discovery required the project team to consider alternative designs for the foundation piles at this location.

The original design, for all of the column foundation T-shaped pile caps, had the four rear piles positioned in a square arrangement (see Fig. 5). The solution to the pipe interference problem was to change this design, with respect to the foundation for column No. 1, to a three-pile single-row arrangement and to place this single row of piles 3 m further back than the original rearmost piles. The shape of the pile cap was changed to a 350 × 988 cm rectangle (see Fig. 5). This was an increase in length of 240 cm from the original cap design. The front, T cross bar, part of the foundation still had five piles arranged in two rows, three piles in the front row and two in the second row, but the width of the bar was reduced by 5 cm. These adjustments moved the impacted rear piles to the side of the drainage pipe, which stayed in

Fig. 12. Drawing of special pier cap (for column number 1) used to avoid drainage pipe
place, and created a pile cap that straddled the pipe. This change also required creating a 1.14 m “step” in the pile cap. The step configuration raised the bottom of the pile cap on the side of the drainage pipe. Fig. 12 shows a section view of the modified pile cap for column No. 1. This solution did not affect the design of the concrete columns. Fig. 12 also shows the positions of the post-tension cables that tied the column to its foundation.

**Project Site Constraints**

The site environment was very constrained. Student housing on the campus of the Technion borders the south and east sides of the site. Therefore, the contractor had a very strict boundary limitation in those directions. To the north of the stadium site was the existing athletic field and to the west were the tennis courts of a private club. The contractor was not permitted to infringe on any of these adjacent properties. These constraints forced the project work and staging into a very confined area. Therefore, organizing and planning the work was very important. Of particular importance was storage of the concrete columns and beams, and positioning of the cranes. The large crawler crane used to lift the columns has a width, outside edge of track to outside edge of track, of 9.5 m and a superstructure length, rear of counter weight to front toe of track, of 12 m (Fig. 2). Fig. 1 shows the limited area of the construction site. The only solution to providing space for the cranes to maneuver was to delay part of the stadium construction until both lifting operations had been completed.

**Athletic Field**

It was a contractual commitment, that during construction of the stadium, work activities could not disturb the regularly scheduled use of the athletic field. Therefore, neither equipment nor material could be stored on the sports field. Workers were not allowed to even enter the track and field area and it was a contractual requirement that the contractor build a solid 5 m high fence to limit the possibility of dust from construction operations impeding athletic events.

**Conclusion**

The structural work for this stadium was completed in June 2004. The owner plans to advertise a separate contract for installing the special roof canopy and other finish work within the stadium. Fig. 13 shows a general view of the completed structural work including the concrete columns and beams. Although the work area was very limited in extent, this project was distinguished by the very large concrete elements—column and beams—that had to be cast and stored within the footprint of the structure.

After the work was completed it was noted that the project planning could have been improved, particularly in regard to positioning the large crane and scheduling the work. Too little attention had been given to the best location for the crane in terms of all project activities. Crane planning had located the crane based only on the requirements for making the picks. In respect to that issue the selected location was satisfactory. However, crane planning failed to consider the impact of the selected positioning in regard to other project activities. Crane location affects a project globally. If the crane had been positioned on the other side of the construction site, more area would have been available for the casting of the concrete columns and beams. This impact had not been taken into consideration during the planning process. In a similar manner it was found that the project schedule was unrealistic, since site constraints were not taken into account when the schedule was prepared.

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