Structural and Architectural Designs of the Optimum Alternative for Rio 2016 Olympic Tennis Stadium

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Abstract

The next edition of the Olympic Games is going to be held in Rio de Janeiro, Brazil, in 2016. The city of Rio de Janeiro is currently preparing the venues needed for the event. One of the venues that have to be prepared from scratch is a tennis complex. Signature tennis complexes such as theAll England Club tennis complex in London (Wimbledon) were explored to develop the optimum design of a tennis complex for the 2016 Olympic Games. Basic tennis complexes typically have a main stadium, two smaller stadiums, and several ground courts.This paper presents the. This paper summarizes the explored concepts and methodology as well as detailed structural and architectural designs of the main stadium, taking into consideration mainly safety, aesthetical and economical characteristics. The structural model of the main stadium was developed and verified using innovative software package known as ETABS. In addition, the overall architectural layout for the whole complex was developed using the innovative Autodesk Maya3D software. Information provided by the Brazilian Olympic Committee and the International Olympic Committee were used to define key aspects of the project, such as the location, capacity of the main stadium, and the budget available for the facility. Structural and architectural details of the tennis complex in general and the main stadium in particular are provided.

Keywords: Optimum; Alternative; Structural Design; Rio 2016; Olympic; Tennis; Stadium.

1. Introduction

The city of Rio de Janeiro in Brazil will host the XXXI Summer Olympic Games in August of 2016. Although some of the city's existing facilities are going to be used for the event, 13 major facilities need to be constructed including many other venues need to be constructed including Olympic tennis center to host the tennis competitions. According to information provided by the Rio 2016 Olympic Committee, a total of 16 courts will be provided across a site area of approximately 22 acres. These courts are divided in the following manner: Center Court Stadium (capacity for 10,000 seated spectators), Court 1 Stadium (capacity for 5,000 seated spectators), Court 2 Stadium (capacity for 3,000 seated spectators), 6 Ground Courts (capacity for 250 seated spectators each), and 7 Practice Ground Courts. Construction of the new Olympic Tennis Center will also provide the city of Rio de Janeiro a much needed competition venue for future major tennis events.

Most of the venues that will be used in the Rio 2016 Olympic Games are not yet ready to receive competitions including the Rio Olympic Park, which is the most important competition location for the Olympic Games. The Olympic Park location will be the Circuito de Jacarepaguá racing track, on the shore of the Jacarepaguá Lagoon.

The Olympic Tennis Center location inside the Rio Olympic Park was defined by the Brazilian Olympic Committee as the southeast corner of the Olympic Park, right next to the Jacarepaguá Lagoon shore. A model of the Rio Olympic Park made by the Brazilian Olympic Committee is shown in Fig. 1. The Olympic Tennis Center location inside the Olympic Park is highlithed in red. The Brazilian Olympic Committee has many vision models for the Olympic Tennis Center as shown in Fig. 2(a) and for the Rio Olympic Park itself as shown in Fig. 2(b).

The main goal of this study is to provide detailed structural and architectural explorations, thus asserting the optimum alternative design for the Center Court Stadium. The optimum alternative must be a signature landmark, aesthetically pleasing, safe and comfortable for the public, stable under all loading conditions, easy to construct and maintain, and within the stipulated budget.

2. Research Significance

The Olympic Games is one of the most important international sport events in the world, and its next edition is going to be held in Rio de Janeiro, Brazil, in 2016. This study presents the methodology and concepts for the layout and design of the optimum alternative for the tennis complex in general and the main tennis stadium in particular. The considered factors include safety, aesthetical, economical characteristics, ease of construction, public acceptance, reliability, environmental protection, public comfort, and ease of maintenance. The power of innovative structural and architectural design software packages were combined to develop an eye-catching creative design alternative. It is expected that this study would be of interest to the Olympic Committee, civil engineers, tennis players, and fans all over the world.

3. Description of the Analysis and Design Program

3.1 Requirements and Specifications

According to the Rio 2016 Olympic Committee, the Center Court Stadium must have a capacity for 10,000 seated spectators. Moreover, it must also have a 120ft × 60ft clear space at the center in order to comply with the court spacing requirements provided by the International Tennis Federation (ITF). The steel frame design is based on the American Institute of Steel Construction code (AISC, 2011). The concrete frame design is based on the ACI 318-08code developed by the American Concrete Institute (ACI, 2008). Both designs follow the Load and Resistance Factor Design (LRFD) approach. The loading requirements such as dead load, live load, and wind load are based on the International Building Code (IBC, 2012) and the ASCE 7-05 code (ASCE 7-05, 2005) (Minimum Design Load for Buildings and Structures), developed by the American Society of Civil Engineers (ASCE). The wind speed is based on the norms of the Brazilian Association of Technical Norms (ABNT) and adjusted to account for the importance of the structure and also for safety against any abnormal extreme wind events.

3.2 Design Variables

Many design variables have to be considered for a stadium that is going to host an international event with the importance of the Olympics. Stadiums around the world have various shapes; the shapes considered herein were a rounded shape, a rectangular shape, a rectangular shape with rounded corners, and an octagonal shape. The materials that are going to be used for the construction of the stadium are considered in the design process including steel, concrete, aluminum, and glass. Two major design variables that have to be considered when designing a tennis stadium is whether the stadium will have a cover for the grandstand to protect the public and if there will be a roof to cover the court and protect the players from sun, rain, and strong winds.

3.3 Limitations and Constraints

The Olympic Tennis Center Complex that is going to be built for the 2016 Olympic Games in Rio de Janeiro has a budget of $62.808 million, which was evaluated in 2008 by the Brazilian Olympic Committee. The budget was created to be part of the bid package made by the Brazilian organization to present to the International Olympic Committee in the process of selecting the host city of the event. From the $62.808 million of the budget, the Brazilian Olympic Committee proposed that $46.115 million was going to be directed to the fixed facilities, meaning the Center Court Stadium, Court 1 Stadium, Court 2 Stadium, and the 13 ground courts. The remaining $16.693 million was planned for temporary facilities such as tents for concessions, stores, and restroom facilities. By the time the budget was evaluated, there were no specific budgets for the Center Court Stadium, Court 1 Stadium, Court 2 Stadium, and ground courts.

In order to find a budget for the Center Court Stadium, many aspects were taken into consideration, such as the capacity of seated spectators of each facility, importance of the structure for the event, and previous data from other tennis complexes. Accordingly, from the $46.115 million budgeted for fixed facilities, it was considered that $25 million would be a reasonable budget of the Center Court Stadium, $10 million for Court 1 Stadium, $6 million for Court 2 Stadium, and around $400,000 for each of the 13 ground courts. In order to find out how much of the$25 million budget will be only for the construction materials cost, Brazilian construction specialists were consulted. It was found that approximately 75% of the total cost of a stadium is only the materials cost while 25% is labor cost. Therefore the budget for the materials of the stadium was calculated to be $18.75 million.

In order for the Olympic Tennis Complex to be used in the 2016 Summer Olympic Games in Rio de Janeiro, the International Olympic Committee requires that the facility must be ready to be used in 2015. The facility has to be tested in an event one year in advance so that the International Olympic Committee would make sure that it can host the Olympic Games. The event that the Olympic Tennis Complex is going to be tested for in 2015 is the new tennis tournament created by the Association of Tennis Professionals (ATP) that will begin in 2015; the ATP Rio 500.

3.4 Structural and Architectural Software Packages

The complexity of the design of a stadium requires innovative software packages to model the structure. For analyzing and designing the structure of the stadium there is a need for innovative modeling software package that can analyze and design structural members of various types. For showing the design in a real life perspective there is a need of innovative architectural software that can model the stadium in three dimensions. The selected software packages are: Extended Three – Dimensional Analysis of Building Systems (ETABS, 2013), Autodesk Maya 3D (Maya, 2013), and Autodesk AutoCAD (AutoCAD, 2012). The Autodesk AutoCAD software was used to create a drawing of the side view of the structure and top view drawings for every floor of the stadium (AutoCAD, 2012). The ETABS software was used to model the structure of the stadium, member by member (ETABS, 2013) considering the self-weight of all members as well as other dead, live, and wind loads. It also designs the members using the most economical sections. The Autodesk Maya 3D software was used to make an architectural model of the entire tennis center, in order to show how the stadium will look in real life around the other structures of the complex. Using Autodesk Maya 3D software, it is possible to create an animation with a camera flying around and inside the stadium to have a clear idea of every detail of the structure (Maya, 2013).

4. Conceptual Designs

Four conceptual design alternatives were studied. The first alternative is a simple but efficient stadium as shown in Fig. 3(a). The design has a rectangular shape with concrete stands and chairs fixed to the concrete. It does not have any cover over the stands and roof over the court. The fact that there is no roof or cover maximizes the sun light reception and minimizes the shadows in the court, which is very important for the playability of tennis. The second alternative is a stadium with rectangular shape and rounded corners as shown in Fig. 3(b). The grandstands of the stadium are made out of concrete with chairs fixed to the floor. The outside of the stadium contains glass windows going all around the perimeter of the structure. The glass windows have an illumination system, which changes between yellow, green, and blue (Brazilian flag colors) during night matches. In addition, there is a space between the grandstands and the outside glass for public circulation and also to accommodate restrooms, concessions, and merchandise stores. The third alternative is a circular shape stadium completely covered by an aluminum roof as shown in Fig. 3(c). The interior of the stadium is acclimatized by air conditioning system for the convenience and well-being of the spectators and players. The grandstand is made of concrete and it is continuously rounded all around the court. Under this continuous grandstand, a service area for the spectators is placed, accommodating amenities such as: restrooms, concessions, and stores. The public has access from the outside to the service area through gates, which is then connected to the stands through stairs, elevators, and gates. Finally, the fourth alternative is a rectangular shaped stadium with rounded corners as shown in Fig. 3(d). It has three seating levels, having a fixed cover for the top level of seating similar to the second alternative. This fixed cover does not extend to the two lower levels so that it does not create shadows in the court, which disturbs the players during the matches. In addition to this fixed cover, there is a retractable roof that can be closed in case of inclement weather (rain or high speed winds). Both the fixed and retractable covers are made of aluminum. Since the stadium might be closed due to inclement weather, it has to have an air conditioning system to maintain the temperature at pleasant levels when the roof is closed. The grandstand is made of concrete, with chairs fixed to the floor. Table 1 summarizes the major details of each alternative.

5. Evaluation of the Conceptual Design Alternatives

In order to decide on the optimum conceptual design, the design goals previously stated were ranked in order of importance. A matrix showing the design goals being evaluated and rated in order of importance is shown in Table 2.Relative weight factors from 0 to 100 were given for each design goal based on their importance. Safety, construction cost, and ease of construction were considered as the top priority design goals. Aesthetics, public acceptance, maintenance cost, and reliability were chosen to be of high priority. Finally, public comfort and environmental protection were chosen to be medium priority design goals. Based on importance, the top priority goals were given values from 75 to 100, the high priority values were from 35 to 70, and the medium priority values were from 0 to 30.

The decision matrix is a matrix created to select the optimum conceptual design. The matrix is a comparison between the conceptual designs based on the design goals, which were ordered based on their importance. The four alternatives were evaluated in each design goal; i.e. in each design goal the conceptual designs were compared so that they were ordered from highest to lowest in each category. Furthermore, for each design goal, the alternative that was ranked the highest compared with the other alternatives for a category received a value of 4, the second highest a value of 3, the third highest a value of 2, and the lowest a value of 1. Then, the values between 1 and 4 are multiplied with the weight factor previously given for each design goal. The product is then summed to find out which conceptual design is the optimum alternative as shown in Table 3. The second conceptual design alternative received a total value of 1740 and was chosen as the optimum design.

6. Description of the Optimum Alternative

The structural design of the grandstands composed mainly from a system of reinforced concrete columns, beams, and slabs. The support of the service area corridors is made of a steel system containing floor beams, girders, and columns. The columns are spaced 30 ft (9.15 m) from each other and also support the roof cover. The aluminum roof cover itself is supported by a system of bowstring steel trusses connected laterally with each other. The space between the columns is filled with a glass cover giving a clean and modern look to the stadium. Attached to the glass cover is an illumination system that has the Brazilian flag colors placed to be used during the night to create a beautiful scenario for spectators.

The stadium has mainly four floors, three for the circulation of people and players, and one for the media-broadcasting center. In order to show a top view of each different part of the structure, the stadium was divided into six levels. Level 1 of the stadium is the level dedicated to the players as shown in Fig. 4(a). In this level, the entrance for the players is located in two of the curved portions of the glass cover. From their entrance they can easily access the locker rooms, the trainer's room and the press room for their conferences. After the match, the players have easy access from the court to press mixed zones for quick interviews. The level also contains the entrance for spectators and the corridor for their circulation and access to other floors. Furthermore, there are concessions and restrooms for the convenience of the public. Fig. 4(b) shows Level 2 of the stadium that contains entrances for spectators to the stands, using six corridors strategically located around the service hallway. In this level, the service area corridor for the common public circulation and access to other floors has more concessions and restrooms than Level 1. The access to Level 2 is made from Level 1 through strategically located stairs and elevators. Level 3 of the stadium is the level dedicated for the media broadcasting center as shown in Fig. 4(c). The access to the media center is made through stairs coming from Level 3 and stairs and elevators designated to the media, which are located inside the communications center. The people that are going to be working on the Center Court Tennis Stadium, for broadcasting, will have convenient facilities such as the Media Access Corridor, the Media Communications Center, and Press Boxes. Fig. 4(d) shows the Level 4 of the stadium, whichis very much similar to Level 2. It also contains entrances for spectators to the stands, using six corridors strategically located around the service corridor. In this level, the service area corridor for the common public circulation and access to other floors has the same number of concessions and restrooms as Level 2. The access to Level 4 is made from Level 2 through strategically located stairs and elevators. Fig. 4(e) shows Level 5 of the stadium, which is a level that only shows the third floor of the service corridor for spectators and the complete grandstand of the Center Court Stadium. Finally, Level 6 is the Roof Level. A top view of the stadium shown in Fig. 4(f) shows the court, the first two levels of seating, and the aluminum roof. Fig. 5 shows the orthographic view of the architectural model of the stadium and view of grandstands from access corridor generated using Autodesk Maya 3D (Maya, 2013).

7. Analysis and Design of the Optimum Alternative

The structural system of the stadium can be divided into two major systems connected to each other. The first major structural system consists of columns, beams and slabs, all made of reinforced concrete with compressive strength, $f_c^/$ = 4 ksi (28 MPa) and Grade 60 deformed steel rebars with f_y= 60 ksi (420 MPa). This system encompasses all the three seating levels and the area under them. The second major structural system encompasses the service area corridor as well as the roof cover. The vast majority of the structural members of this second major system are made of W-shape structural steel sections, with the exception of the slab of the service area corridor. Therefore, these two major systems are going to be referred as Concrete System and Steel System. It is important to note that in the Concrete System, the space between the columns is filled with concrete masonry units (CMU), but they do not have any structural relevance. Moreover, in the Steel System there are also other materials used which have no structural significance for the system. They are the aluminum cover for the roof and the exterior glass finishing of the stadium. Although the aluminum cover and the glass finishing have no structural contribution to the system as a whole, they still meet the requirements for their individual loads.

7.1 Stadium Loads

The stadium is designed taking into consideration three different types of loads: dead, live, and wind loads. Seismic loads that are commonly considered in the design of complex structures are not considered herein since Brazil is a country located right in the center of a single tectonic plate, therefore not having any historic seismic events. In addition, its climate is fairly warm, especially in the city of Rio de Janeiro, which does not have any history of snow events. The ASCE 7-05 code (ASCE 7-05, 2005) specifies that stadium and arenas with fixed seats (fastened to floor) shall consider a uniformly distributed load of 60psf (2.87 kN/m^2). The 60psf (2.87 kN/m^2) code requirement was magnified by 30% to account for impact loads (dynamic loads) that may be caused by the spectators. Therefore, a uniformly distributed load of 78psf(3.73 kN/m^2) is assigned to the slabs that are directly under the stands. For the slabs where people will be walking, a 100psf(4.78 kN/m^2) live load is considered, which is a typical value used for structures with high importance such as stadiums and hospitals and it is in accordance with the minimum requirements specified by the ASCE 7-05 code (ASCE 7-05, 2005). Lastly, for the slabs that will be directly under the concessions area and areas used as storages, a 125psf(6.0 kN/m^2) uniformly distributed load is considered, which is the value required by the IBC (IBC, 2012) and ASCE7-05 codes (ASCE 7-05, 2005) for light storage warehouses.

As mentioned earlier in this section, the only lateral load considered in the design is the wind load. In order to calculate the wind load, the design wind speed must be first determined. The IBC (IBC, 2012) and ASCE (ASCE 7-05, 2005) codes only give wind speed contour maps for regions in the United States. Therefore, in order to determine the design wind speed in Rio de Janeiro, a contour map provided by the Brazilian Association of Technical Norms was used. Rio de Janeiro is represented falls in the region named “Região II”, which is determined to have design wind speeds of 80mph (35m/s). Due to the importance of the structure and to account for any abnormal wind events, this design wind speed was increased by 50%, which led to a final design speed of 120mph (52.5 m/s). Since the wind load can be in any direction, the two extreme cases where the load is acting perpendicular to the long direction and perpendicular to the short direction of the stadium are considered. The calculated wind pressure based on the ASCE code (ASCE 7-05, 2005) is 36 psf (2.87 kN/m^2) at a height of 72 ft (22 m). It was assumed that the wind load decreases linearly from 36 psf (2.87 kN/m^2) at the top of the stadium to zero at the bottom. Since the stadium is symmetric, each side is assumed to carry half of the wind load.

7.2Structural Concrete System

Figure6 shows a side view of the Concrete System. All the beams have a designation starting with "B" followed by a number, depending on the location of each beam. Following the same logic, all the columns have a nomenclature starting with a "C" followed by a number and all the slabs have a designation starting with "S" followed by either a number or a combination of one letter and one number, used to indicate the location of them. In this system, both the dead and live loads are applied to the slabs. Majority of the slabs are simply supported and transfer the loads to floor beams located at their edges, with the exception of S1, S2, and S3. Slabs S1 and S3 are simply supported as well, but they have beams only at one of their supporting edges, with the other edge being supported by slab S2. On the other hand, slab S2 is a cantilever, being supported directly by column C2. Moreover, all the beams are simply supported by columns located at their ends.

The reinforced concrete slabs vary in thickness, depending on the amount of load that each one is carrying, but they all use the same steel reinforcing rebars, with the exception of the slab SC, which is located in the corridor of the service area. All the slabs use #6 (No. 19) rebars for the main reinforcement and #4 (No. 13) rebars for the shrinkage and temperature reinforcement, except slab SC, which uses #5 (No. 16) rebars for the main reinforcement. The use of the same bar size for all the slabs is intentionally made to decrease the construction cost. Table4 shows a summary of the final design details of all the slabs.

The rectangular reinforced concrete beams also have varying depths and widths depending on the load that each one is supporting, but they share the same reinforcing bar sizes. For the main reinforcement, either #7 (No. 22), #8 (No. 25), or #9 (No. 29) rebars are used, while the stirrups are all of size #3 (No. 10). In some of the beams that carry loads in both lateral and vertical directions, a combination of more than one rebar size were used, but they are restricted to the same set of either #7 (No. 22), #8 (No. 25), or #9 (No. 29) rebars. Table5 shows a summary of the final design details of all the beams. Finally, all the columns have a square cross-section and their lateral reinforcement is made with lateral ties. Although the cross-sectional dimensions change from one line of columns to another, all the columns on the same line (on top of each other) are set to have the same cross-sectional dimensions. In addition, the longitudinal reinforcement uses only either #8 (No. 25) or #9 (No. 29) rebars for all of the columns, while the lateral ties are all size #3 (No. 10). Table6 shows a summary of the final design details of all the columns.

7.3Structural Steel System

The Steel System is resisting three different types of loads: the first one is the load coming from the aluminum roof, the second is the one coming from the corridor slabs, and the third one is the lateral wind load. Figure 7 shows that the steel system is mainly composed of: bowstring trusses supporting the aluminum roof with purlins and X-bracing members connecting the trusses; exterior columns supporting part of the load from the truss and the loads coming from the girders; floor beams supporting the slab of the service area corridor; exterior girders supporting the floor beams; and exterior X-bracing lateral resisting system. It is important to note that the floor beams are simply supported. The other supporting beams are beams B13 and B15 that are shown in the Concrete System. All the structural steel members have W-shape sections. Although there are different sizes of W-shape steel sections used for the members, using the W-shape for all columns can reduce the construction cost and simplify the constructability. Table7 shows a summary of the final design details of all the structural steel members.

7.4Modal Analysis

Modal Analysis was performed to check the natural frequency of the stadium and to compare it with the expected frequency from human activities. The self-weight of the structure is used as a mass source in the modal analysis. The first three mode shapes were checked to ensure the stability of evey member of the stadium. The natural frequency of the first mode shape was much higher than the frequency that may occur when assuming that spectators are jumping on the stadium (up to 2.2 cycles/second). Therefore the stadium can be considered structurally adequate and stable under the influence of dynamic loads. Figure 8 shows the first two mode shapes.

8. Cost Calculation

After the design of the stadium, the cost for each single member of the structure was calculated. For enhanced accuracy, the cost of the materials was found with the help of a Brazilian construction company specialist. The prices of the materials in Brazil are calculated using the metric system. The costs in Brazil are evaluated as follows: the cost of concrete is priced in cubic meters of concrete, the cost of steel is priced in kilograms of steel, the cost of glass is priced in squared meters of glass, the cost of aluminum panels is priced in squared meters of aluminum, and the cost of the CMU is priced in squared meters. From the method used to price the materials in Brazil, each member of the structure was evaluated in the unit needed to calculate its cost. The prices for materials were first evaluated in Brazilian currency, Reais, and then converted to US Dollars in a rate of 2. This currency exchange value was used since the currency exchange fluctuates normally around 1 US Dollar for 2 Brazilian Reais. A summary of the materials cost for the stadium is shown in Table 8.

In the United States, the material cost is only around 30% of the cost of construction. Labor is the most expensive aspect in the construction, because the minimum wages for workers are quite compensating. In countries where minimum wages are low, such as Brazil, the cost of the materials is almost the same or sometimes even larger than the cost of labor.

Researching with specialists from the construction field in Brazil, it was found that approximately 45% of the cost of the stadium will be materials cost, and approximately 55% is labor cost. Therefore, it is possible to say that if the total cost of materials is $8,055,188.44, the total cost of the stadium would be around $18 Million. This estimated cost of the stadium is under the stipulated budget of $18.75 Million.

9. Summary and Conclusions

This paper summarizes the systematic methodology for designing the major tennis stadium for Rio de Janeiro 2016 XXXI Summer Olympic Games. The design followed the most recognized international general building codes and design codes taking into consideration many aspects obtained from the Brazilian Olympic Committee. Innovative software packages were used in the architectural and structural designs. The optimum design alternative satisfied all of the requirements, specifications, limitations and constraints in terms of safety, aesthetic, economy, ease of Construction, public acceptance, reliability, environmental protection, public comfort, and ease of maintenance. The stadium was designed to withstand dead and live loads considering dynamic effects as well as abnormal wind loads. In addition, the stadium fundamental frequency of the first mode of vibration was much greater than a potential high frequencies resulting from jumping of the spectators. Using Brazilian prices to calculate material and labor costs, the final cost of the main stadium was estimated to be around $18 million, which is below the proposed budget of $18.75 million by the Brazilian Olympic Committee.

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Table 1: Alternative Comparison Matrix

Alternative	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**
Shape	Rectangular	Rounded	Circular	Rounded
Stands Material	Concrete	Concrete	Concrete	Concrete
Outside Structure Material	Concrete	Steel and Glass	Steel	Steel
Cover	None	Partial	Complete	Retractable
Cost	Low	Moderate	High	Extremely High
Ease of Contraction	High	Moderate	Low	Low
Maintenance Cost	Low	Low	High	Extremely High
Aesthetically Pleasant	No	Yes	Yes	Yes
Service Area	No	Yes	Yes	Yes
Shadows on Court	Low	Moderate	No	Moderate
Interaction with Environment	Yes	Yes	No	Yes

Table 2: Design Goals Rank – Ordering Matrix

Design Goals Rank-Ordering	A	B	C	D	E	F	G	H	I
Safety (A)	-	0	0	0	0	0	0	0	0
Construction Cost (B)	1	-	0	0	0	0	0	0	0
Maintenance Cost and Ease of Maintenance (C)	1	1	-	1	1	0	0	0	1
Public Acceptance (D)	1	1	0	-	0.5	0	0	0	1
Aesthetics (E)	1	1	0	0.5	-	0	0	0	1
Reliability (Weather Influence) (F)	1	1	1	1	1	-	0	0	1
Environment Protection (G)	1	1	1	1	1	1	-	1	1
Public Comfort (H)	1	1	1	1	1	1	0	-	1
Ease of Construction (I)	1	1	0	0	0	0	0	0	-
Total	8	7	3	4.5	4.5	2	0	1	6

Table 3: Decision Matrix

Criteria and importance Factors	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Safety (100)	1	3	4	2
Construction Cost (95)	4	3	2	1
Ease of Contraction (85)	4	3	1	2
Aesthetics (70)	1	4	3	2
Maintenance Cost and Ease of Maintenance (60)	1	4	2	3
Public Acceptance (70)	4	3	2	1
Reliability (Weather Effect) (40)	1	2	4	3
Public Comfort (25)	1	2	4	3
Environment Protection (10)	4	3	1	2
Total	1305	1740	1415	1090

Table 4: Summary of Final Design of Concrete Slabs (1 in. = 25.4 mm)

Concrete Slabs Summary			Main and Minimum Reinforcement	
Slab ID	Location	Thickness, in.	Main Bars	Minor Bars
S1	Staircase of First Level	9	#6 at 12″	#4 at 12″
S2	Between First and Second Level Staircases	18	#6 at 6½″	#4 at 6″
S3	Staircase of Second Level	18	#6 at 6½″	#4 at 6″
SF2	Second Story Floor	18	#6 at 6½″	#4 at 6″
S4	Over the Media Space (corridor for third level)	14	#6 at 8″	#4 at 7½″
S5	First Section of Staircase of Third Level	14	#6 at 8″	#4 at 7½″
S6	Second Section of Staircase of Third Level	14	#6 at 8″	#4 at 7½″
SF3	Third Story Floor	14	#6 at 8″	#4 at 7½ ″
SFM	Media Story Floor	14	#6 at 8″	#4 at 7½ ″
SC	Service Area Corridor (Steel System)	5	#5 at 12″	#4 at 12 ″

Table 5: Summary of Final Design of Concrete Beams (1 in. = 25.4 mm)

Beam	Location	Depth, in	Width, in	Cover to rebar center, in	Main Reinforcement	Stirrups
B1	Support Bottom of Staircase of First Level	20	12	2	3 #9 (y-bending) 2 #7 (x-bending)	#3 at 9″
B2	Left Support of Slab S4 (corridor for third level)	16	8	2	2 #8	#3 at 7″
B3	Right Support of Second Level of Stairs and Left Support of Slab SFM	30	16	2	5 #9 (y-bending) 3 #9 (x-bending)	#3 at 7″
B4	Support for Two Slabs SF2 (under column C4)	32	16	2	5 #9	#3 at 6½″
B5	Support Slabs S4, S5, and SF3 (corridor for third level)	30	16	2	5 #9 (y-bending) 2 #8 (x-bending)	#3 at 6½″
B6	Support Two SFM Slabs (under column C6)	28	12	2	3 #9	#3 at 12½″
B7	Support for Two SF2 (under column C7)	26	16	2	5 #9	#3 at 8½″
B8	Support Slabs S5 and S6 (middle of third level)	30	16	2	5 #9 (y-bending) 2 #8 (x-bending)	#3 at 6½″
B9	Support for Two SF3 (under column C9)	26	16	2	5 #9	#3 at 6″
B10	Support for Two SFM (under column C10)	26	16	2	5 #9	#3 at 6″
B11	Support for Two SF2 (under column C11)	32	16	2	5 #9	#3 at 7″
B12	Support Slab S6 and Column C17 (top of third level)	32	18	2	6 #9 (y-bending) 3 #7 (x-bending)	#3 at 15″
B13	Support Slabs SF3 and SC (Under column C13)	26	16	2	5 #9	#3 at 12″
B14	Support for SFM. (under column C14)	28	12	2	3 #9	#3 at 13″
B15	Support Slabs SF2 and SC (under column C15)	26	16	2	5 #9	#3 at 10″

Table 6: Summary of Final Design of Concrete Columns (1 in. = 25.4 mm)

Column ID	Location	Size (in x in)	Longitudinal Reinforcement	Lateral Ties
C1	Support Beam B1 (bottom of staircase of first level)	14 x 14	4 #9	#3 at 12″
C2	Support Slab S2 (between first and second level)	24 x 24	12 # 9	#3 at 18″
C3	Support Beam B2 (exterior of media)	24×24	8 # 8	#3 at 16″
C4	Support Beam B3 (top of second level)	24×24	12 #9	#3 at 18″
C5	Support Beam B4 (first story)	24×24	8 #8	#3 at 16″
C6	Support Beam B5 (bottom of third level)	20×20	8 #8	#3 at 16″
C7	Support Beam B6 (interior of media)	20×20	4 #9	#3 at 18″
C8	Support Beam B7 (first story)	20×20	4 #9	#3 at 18″
C9	Support Beam B8 (middle of third level)	20×20	4 #9	#3 at 18″
C10	Support Beam B9 (media story)	20×20	4 #9	#3 at 18″
C11	Support Beam B10 (second story)	20×20	4 #9	#3 at 18″
C12	Support Beam B11 (first story)	20×20	4 #9	#3 at 18″
C13	Support Beam B12 (top of third level)	28×28	12 #9	#3 at 18″
C14	Support Beam B13 (media story)	28×28	8 #9	#3 at 18″
C15	Support Beam B14 (second story)	28×28	8 #9	#3 at 18″
C16	Support Beam B15 (first story)	28×28	8 #9	#3 at 18″
C17	Support Bowstring Truss	12×12	4 #8	#3 at 12″

Table 7: Summary of Final Design of All Steel Members

Steel Member Type	Section
Top Chord of Trusses	W8×10
Vertical Members of Trusses	W8×13
Truss Bracing Members	W8×24
Bottom Chord of Trusses	W8×28
Diagonal Members of Trusses	W8×31
Truss Purlins not in the Lateral Resisting System	W8×35
Truss Purlins in the Long Direction of the Lateral Resisting System	W10×33
Truss Purlins in the Short Direction of the Lateral Resisting System	W10×49
Exterior Columns	W10×45
X-Bracing Members of Lateral Resisting System (Short & Long Direction)	W12×65
Floor Beams	W14×43
Girders in the Lateral Resisting System (Short & Long Direction)	W16×77
Girders Not in the Lateral Resisting System	W24×55

Table 8: Cost of Materials for the Structure of the Stadium

Material	Price, $/unit	Quantity	Total Cost, $	Final Cost, $
Concrete	206.66 $/m^3	11282 m^3	2331676	8055188
Steel Rebar’s	0.35 $/kg	546073 kg	189760	
Steel Members	6.50 $/kg	681874 kg	4432180	
Glass for Windows	71.03 $/m^2	7328 m^2	520533	
Glass for Media	158.73 $/m^2	330 m^2	52331	
Concrete Masonry Unit (CMU)	29.68 $/m^2	8964 m^2	266062	
Aluminum Cover	45.30 $/m^2	5798 m^2	262646	

Figure 1: Location of the Olympic tennis complex on Rio Olympic Park

Figure 2: (a) Brazilian Olympic Committee Vision Model of the Olympic Tennis Center; and (b) Brazilian Olympic Committee Vision Model of the Rio Olympic park

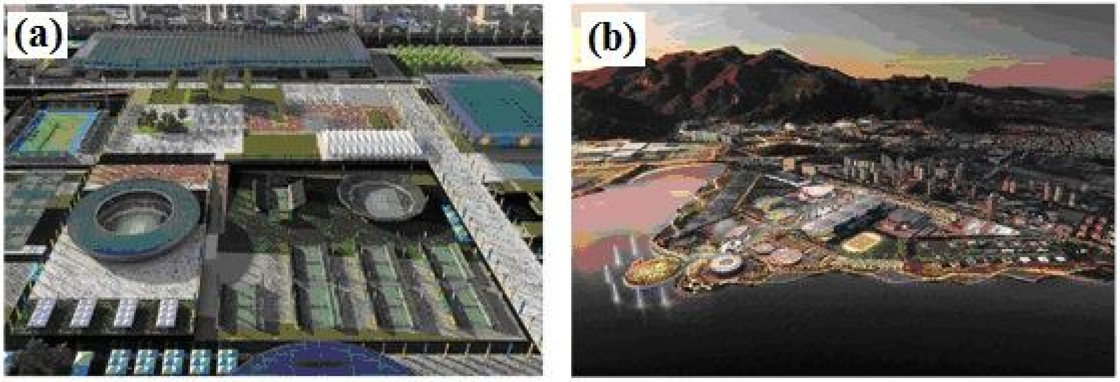

Figure 3: Example of Conceptual Design (a) Alternative 1; (b) Alternative 2; (c) Alternative 3; and (d) Alternative 4.

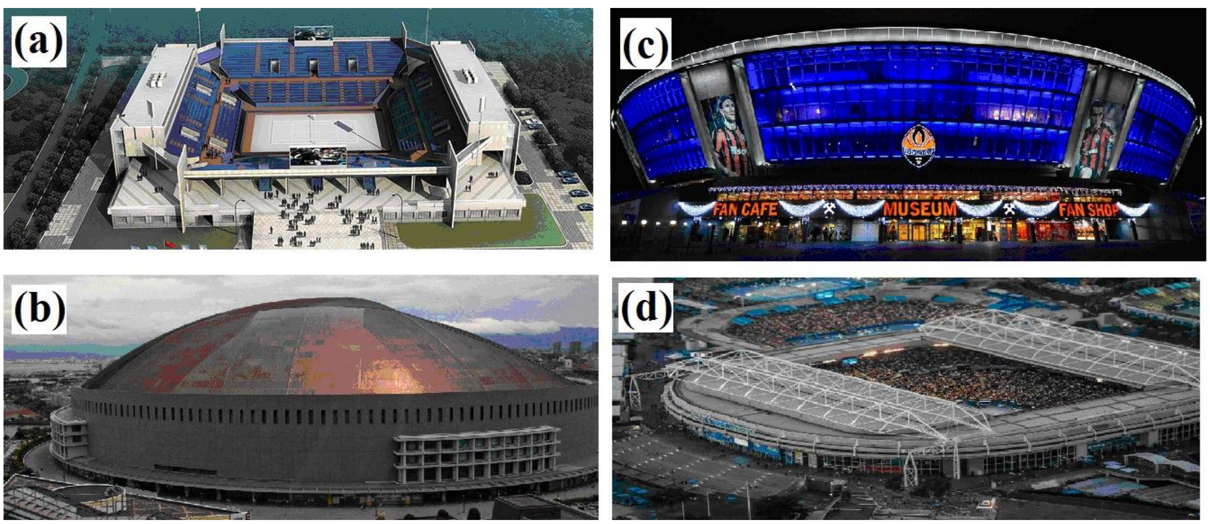

Figure 4: Top View of (a) Level 1, (b) Level 2, (c) Level 3, (d) Level 4, (e) Level 5, and (f) Roof Level

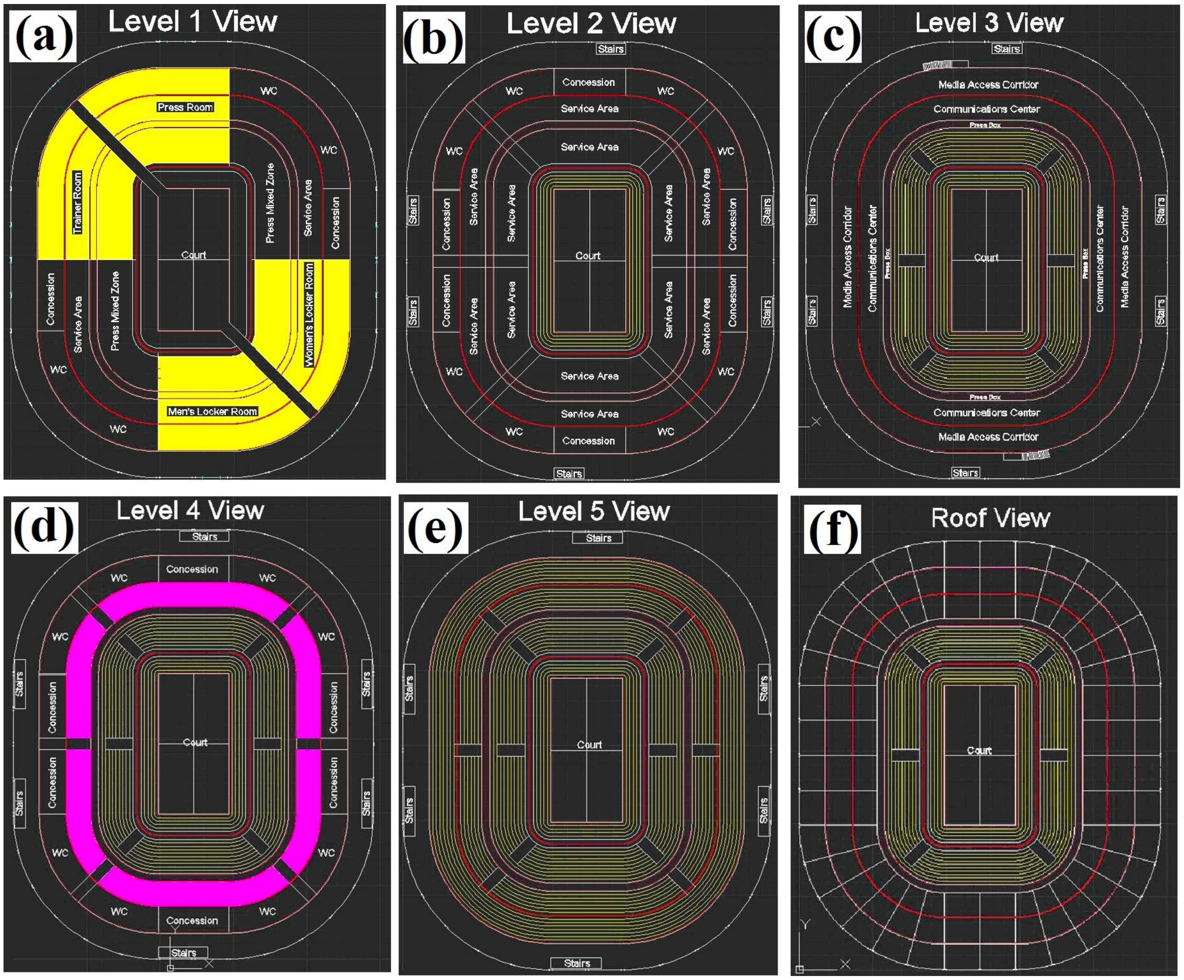

Figure 5: (A) The Orthographic View of the Architectural Model of the Stadium, and (B) View of Grandstands from Access Corridor

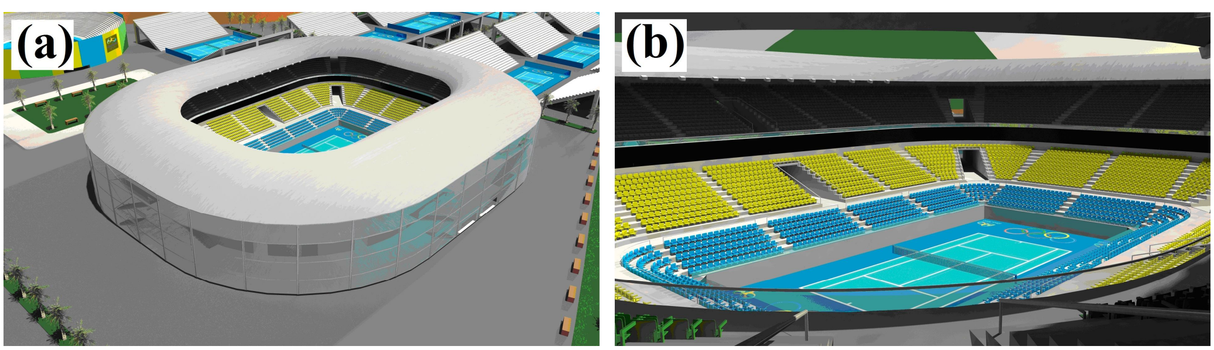

Figure 6: Concrete System Description

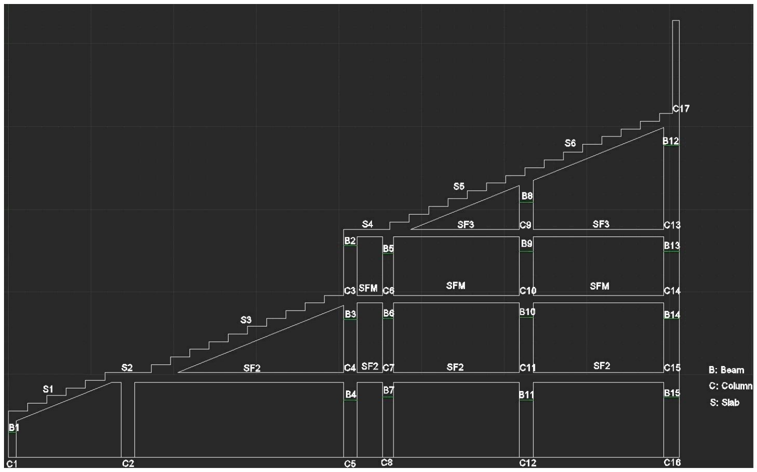

Figure 7: Steel System Description

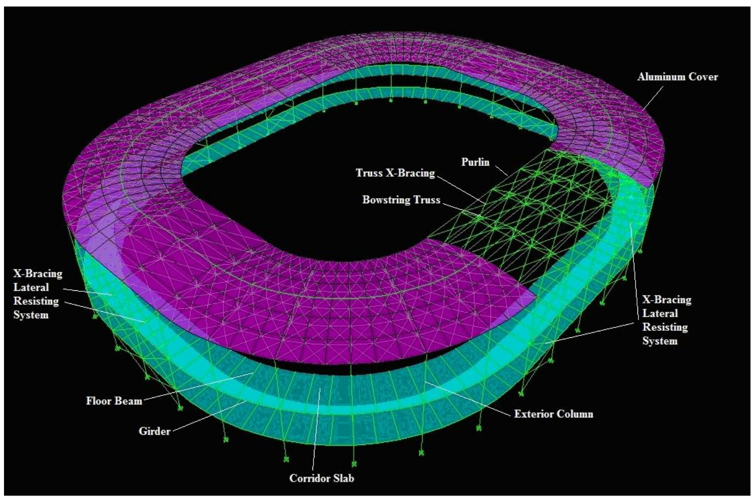

Figure 8: (A) First Mode Shape, and (B) Second Mode Shape