Singapore National Stadium Roof
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Abstract

The case study focuses on design of the Singapore National Stadium roof and its architectural and structural constraints. The dialog between performance form generation and aesthetics was challenged through several design iterations and is critically reviewed in this paper. The collaboration of engineers and architects gave a form to this significant building that was slightly changed several times due to various conditions. The complex shape of the dome structure was resolved in one parametric model that could react on aesthetical and structural requirements. The landmark roof structure generated in computer had to be evaluated by designers and presented to decision making bodies.
1. Introduction

Recently there were discussed many possible ways of architectural designing through computation. Computer design has been established in many architectural practices that react on this phenomenon differently and build their own workflow and guide lines. This paper focuses on techniques of parametric design and its immediate assessment during the design phase. While form generation depends on synthesis of initial information form evaluation depends on criteria known before or discovered during the process of design [1]. Increasing use of advanced associative software packages in architectural practices helps quick evaluation of the design but also enables links with other design disciplines. The design process could involve complex procedures that help to generate and also evaluate the design in real time. Use of parametric software has positive and negative tasks connected with development of a virtual model [2] and there are also issues with integration to a design process and subjective evaluation.

The case study for exploration of form generation and design evaluation is roof of the Singapore National Stadium developed in collaboration of ArupSport architects and engineers, Arup and Arup Associates. The winning competition design was presented in 2007 and featured truly multidisciplinary approach to strong architectural form. The design development of the stadium continued to 2009 and its final form was presented in April 2010. The complex dome structure documents various design decisions based on performative criteria (e.g. structural, dynamics of rain falls), program fulfilment and aesthetics. The whole process was driven by consequent sequences of balanced decisions based on values and design experience. The roof as discrete building component gave opportunity to test and explore possible techniques of architectural design discussed in theoretical examples. The designers were engaged with design environment of the design and build type of contract which was constrained by time and available material and human resources. Although the computer played significant role in this design task an idea from beginning of the computer design age of fully optimised structure [1] was not achieved. The NST roof serves as a showcase of form driven by multiple criteria and decision taking.

2. Project Description

The Singapore National Stadium will form the centre piece to the new Singapore Sports Hub, a complex of sports and leisure buildings currently under construction close to the heart of Singapore. The design ambition from the start of the project has been to create a sustainable, fully integrated sports, entertainment and lifestyle hub for everyone.

When completed in 2014, the Sports Hub will provide
- a new 55,000-capacity National Stadium with a retractable roof and comfort cooling for spectators
• a 3,000-capacity indoor world tournament standard Aquatic Centre, expandable to 6,000 capacity for specific events;
• a 3,000-capacity Multi Purpose Indoor Arena (MPIA) which will be scalable and flexible in layout;
• 41,000 sq m of commercial space with a retail mall of 36,000m²
• a Water Sports Centre catering to elite athletes as well as the public
• the existing 12,000-capacity Singapore Indoor Stadium
• Sports Information & Resource Centre (SIRC), with sports library and museum.

The National Stadium roof is the element that unites all parts of the architectural master plan. With a span of over 312m the roof form provides shade and shelter to the 55,000 seating bowl, ticketed concourse areas and a publicly accessible street – the Sports Promenade – that will be open to public 24 hours a day throughout the year.

The National Stadium roof will be an iconic silhouette in the city skyline, both day and night (Figure 2 shows image of the National Stadium in context of the SIS – Singapore Indoor Stadium). The two forms of the SIS and the great new dome of the National Stadium rises above a two storey plinth whose massing steps back from the waterfront. Both primary forms develop out of a circular landscape setting, establishing a resonance with the history of the

Figure 1. The master plan of the Singapore Sports Hub with the National Stadium in the central location
site. However, the defining moment occurs when the great dome opens, to address the city across Marina Bay.

Nowhere else in the world has such a dynamic connection and image been achieved, across the centre of a major, global city. At a diameter of 312m and a height of 80m, the National Stadium dome will be the largest in Asia and one of the largest of its type in the world. Yet this scale is achieved with minimal means and incredible delicacy of structure and envelope.

With a range of flexible sports venues, each designed to suit a different scale of event, the Singapore Sports Hub will set a new standard in stadium design and in design of integrated sports complexes. The success of the project will be testament to the vision of the Singapore Sports Council which required bidding teams to put together an integrated team of stadium designers, master-planners, event operators, venue managers and builders during the competition stage of the project.

When complete the Sports Hub will offer Singapore the capacity to stage both major, international sporting and city-scale entertainment events. At the same time, it will stimulate public life during non-event days, by integrating the highest standard of sports facilities, alongside attractive, leisure activities, for use by the local community every day. The Sports Hub will reinforce Singapore’s position as a major international sports destination, following the success of events like the F1 and the Youth Olympic Games.
3. Design Requirements

The form of the dome is a direct response to the local climate in Singapore and provides a sustainable response to the environmental challenge of building a stadium in a tropical climate.

Rain protection

Of critical importance to the new stadium was to achieve a design that could provide a guaranteed event schedule. The existing Kallang stadium (recently demolished) was not able to provide this security as the majority of its seats were uncovered. Modern international sports and entertainment events would not be attracted to this type of venue especially when TV rights and advertising rights related to an event have been sold. The national stadium roof achieves this objective in three ways

- a moving roof provides a fully covered arena
- the dome form of the roof is a natural form for shedding large quantities of water
- to the Sports Promenade giant PTFE louvers provide a rain protected access zone outside of the stadium ticket line with rain protected walkways linking to the adjacent MRT stations.

Solar shading, humidity and spectator comfort.

A significant part of the comfort criteria for spectators, required by the client brief, will be achieved through the solar shading provided by the large dome envelope. The comfort criteria achieved through

- the integration of a moving roof which provides a fully covered arena with all spectators gaining shade from the ETFE clad lightweight moving roof. The roof will close prior to an event to ensure that the concrete mass of the stadium bowl is not exposed to solar heat gain.

Figure 3. The relationship of the arching roof trusses and seating bowl.
• the fixed roof cladding provides an insulated aluminium clad reflective surface which ensures that radiant heat affects are minimised
• every seat within the stadium bowl is provided with a low energy comfort cooling which ensure that spectators can enjoy performances in acceptable temperature and conditions.
• to the Sports Promenade giant PTFE louvers provide a sun shaded street whilst allowing for UV light to ensure plant growth to the internal elevation of the stadium.

Spatial / functional requirements
• the roof form also had to satisfy several functional and spatial requirements of the following the 3d geometry of a 55,000 seating bowl optimised for both football and athletics viewing
• height restrictions imposed upon the site due to aviation traffic to the nearby military airbase.
• sun light and ventilation requirements for the sustained growth of a natural turf football pitch.
• viewing requirements for both sporting and non-sporting events. A moving roof was required to allow for spectators to view event spectaculars outside of the stadium – including airplanes "fly pass", fireworks and parachutists (landing on stadium plaza to the open end of the stadium).

The design of the stadium started with addressing brief needs through bowl design. The special parametric design tool developed by J Parrish gave initial form of the stadium bowl and its reconfigurable interior. The bowl reacts on criteria of different program and therefore has variable geometry of the lower tier. The outer boundaries of the elegant 3 tier bowl gave initial set of parameters for the form of the roof. The outer perimeter of the last seating row is elliptical in plan and pushes the boundary condition of the seating bowl as close to the roof soffit as possible (as shown on Figure 3).

All these conditions meet structural criteria for large span structures. Structural challenge is to design a robust and elegant roof with minimal amount of material and achievable building cost. The design team developed series of digital experiments that drove the geometrical form of the roof. The multidisciplinary approach was significant especially in developing the architectural form informed by direct structural feedback [3].

4. Shell Structure

The fixed roof structure is an elemental shell structure in structural steel. The main structural action is that of a 3D shell structure but it is comprised of several interlocking fabricated steel arches rather than a continuous surface. The primary load path is a combination of axial loads and bending in the arched elements which in turn thrust against a perimeter ring beam. The roof has reflecting symmetry about the long axis of the seating bowl and is
asymmetric about the short bowl axis to enable a largely uninterrupted view towards the downtown area of Singapore across the water. There are 6 arches that span in a transverse direction across the long axis of the seating bowl. These arches support the tracks that carry the retractable roof. These trusses are the only structure visible across the void created by the retractable roof. There are then several other interlocking arches that complete the fixed shell structure. The arrangement of the primary structure within the roof creates an intricate geometry that spreads the loads out in different directions to increase structural efficiency and optimise structural depths. The interlocking arches that form the elemental shell structure produce a structure with inherent stability and redundancy.

All structure is controlled by two surfaces defining top and bottom structural chords. The top surface is a sphere with radius of 208m and bottom surface is a torus with diameters 212.56m and 214.52m (Figure 4). The depth of the roof tapers from top to bottom and visual impact of the structure gives the set out of the torus surface on the bottom of the dome. The arcs defining set out of structure taper from 2.5m at the base to 5m at the top of the roof along the central short axis of the stadium. The 6 runway arches are formed from a triangular steel section that is about 3.5m wide on top of the dome and maintains the same aspect ratio of depth to width.
width as they taper to their supports. This ratio (width = 0.8 \times \text{depth}) is a critical parameter which sets out widths of the trusses and controls the visual impact of the roof – Figure 5. The Figure 6 shows the global relationships of the arching trusses and helper spheres that define constant width at truss intersections.

Primary trusses are triangular shaped tubular trusses with some plain tubular trusses used for the secondary structural elements. The panels between the truss elements will be of a tubular space-frame form and will integrate with the cladding system. This secondary structure is a space frame that supports both the lower cladding surface and the upper cladding surface. The top cladding surface forms the waterproof and insulation layers required for climate control. The trusses projected onto a cladding surface form a network of open gutters to direct water on surface of the dome. The water is also directed down to the roof structure where it is collected and brought out of the roof through pipes inside the trusses. At the extremity of the fixed cladding is also a perimeter gutter which collects and distributes the surface water from the main roof to the two ends of the stadium. Below this gutter is a series of louvers formed in a structural fabric (PTFE coated glass fibre was chosen as material).

The stadium roof structure is supported wholly from the top of the podium structure on a perimeter beam, which is defined by a circle on plan and is approximately 311m diameter. As the arched roof structure features
relatively low curvature, the horizontal thrusts generated at the base of the arches are significant. The ground conditions are poor and it is preferable to tie the arch bases together rather than transmitting any horizontal loading to the foundation structure. The arrangement is a tension ring beam linking all the arch bases together. This ring beam is formed from prestressed concrete structure located at the external concourse level and runs around the perimeter of the external concourse. The ring beam is supported on a series of paired columns which also carry the vertical loading from the roof arches. Due to the continuous nature of the ring beam and shell action of the roof there are no movement joints in the main fixed roof structure. The ring beam and supporting columns act as a vertical portal frame and cantilevers to resist any destabilising loads applied to the ring beam.

5. Structural Input

The initial concept of the dome structure is developed through many iterations of digital form-finding by ArupSport structural team. The team considered different geometrical scenarios of the runway and arching trusses. Also the loading by sliding panels of the moving roof is an important input for the design. There were executed many options through iterative
processes involving different software packages for geometry generation and structural analysis. The feedback loop between Digital Project, Rhinoceros and GSA enables to decide positions and dimensions of the main and secondary structure (GSA is a software package from company Oasys for analysis and design of structures). The process was fully parametric and therefore easy to control by designers. The model was always kept live to accommodate structural and architectural inputs. Figure 7 documents testing scenarios from initial form-finding and plots of compression (columns A) and bending forces (column B).

The proposed structural scheme influenced the architectural vision of articulated sculptural roof in its member sizes and also by its logic. The dialog between architectural idea of slender and elegant 3 dimensional structure was deployed in dome trusses.

Among others there are two main requirements on shell trusses from aesthetic point of view: all the crossing arches have to have same widths at intersections and bottom chords have to meet at one point. The desired
solution from architects is that all triangular beams would be normal to outer spherical surface. This would result in appealing junctions of trusses and also its sizes would gradually decrease in size as the roof slopes down. However this solution was modified by structural requirement due to insufficient geometrical relationship of runway trusses for support of the moving roof panels. There was developed grid logic for guiding the structural members on the sphere. One set of grid is parallel to bowl axis in short direction whilst the other direction is developed radial to the sphere. The position of truss sections is then “vertical” as oppose to bottom chords are then always vertical to normal. This rule is applied to all trusses across the fixed roof. The centrelines of the top chords of trusses are arcs on top sphere and centre lines of bottom chords belong to lower surface. The Figure 8 shows the final solution by architects and Arup structural designers. The arches forming the primary structure form a grillage that in turn supports secondary structure.
6. Dome Articulation

Control of the roof in parametric software is critical for rapid changes of design intend and therefore form of the building [5]. The model itself has several layers that interact with each other and allow easy manageability. The flow of work could be regarded as spiral considering positions of trusses, node options and buildability of the roof. The roof design worked with many variables such as number and position of runway trusses, position of transverse trusses (Figure 9 shows geometry of the truss to
roof opening in direction of the bowl long axis), position and geometry of interceptor truss (Figure 9), number of intersection of arching trusses with runway trusses and relationship to cladding of top and bottom surfaces.

The arching trusses changed its number from 5 to 6 and roof became symmetrical for its clear architectural form and constructability. Part of this process is documented on Figure 10 and involved major geometrical changes of the roof. This process happened in a fast process of design and was supervised by structural engineers. Figure 11 shows the live parametric architectural model of structural members. The new shape of the dome was generated approximately every 2nd day for a period of about 2 months and was assessed by the design team on 3d models and renders. Any direct objective feedback in any form of analysis was not achieved and this would be a future challenge of the design team. Although the feedback was not a numerical check through exact values the design was carefully kept within boundaries established by initial form-finding. Described logic of work seemed to be only achievable within constraints of the program. The final structural evaluation confirmed the correct shape and dimension of the proposed form. The challenge of computational approach to both spatial design and layout for structural performance [4] was tackled in this
exercise. The computational optimisation methods were not fully engaged and decisions were primarily based on visual and empirical methods.

7. Moving Roof

The action of moving the roof elements reveals the immediate vicinity of the Stadium Plaza, a large civic space overlooking the Kallang basin, where people can congregate under the shady environment it offers, or enjoy the restaurants and views. But looking further out across the landscaped roofs beyond and over the Kallang Basin, we see the dramatic skyline view which makes this Stadium unique. It is perfectly framed between the elegant curved edges of the roof, and will be visible to all the spectators within the stadium. As a backdrop to sporting events, concerts or the National Day Parade, this visual feature is unrivalled and will be a major advantage in the world sporting arena.

The opening roof is the result of a highly innovative structural solution and despite the scale and height of the structure, it has been designed to open or close efficiently to suit the occasion. Two panels each 210m long and 49 m wide are supported on a set of bogies. The bogies are mounted on four parallel sets of runway beams attached to the fixed roof. Careful attention to design details is needed to ensure wind loads are carried from the retractable roof to the fixed structure. And similarly the roof has to
resist upward pressure of 1.4 kPa (which is the same for downward wind). A fully sealed interface between the fixed and moving roof is not envisaged but the interface shall however prevent blown or driven rain entering the inside of the stadium. A waterproof seal is required between the two halves of retractable roof to prevent rain ingress at this point when the roof is in the closed state.

The panels articulated by pattern are significant urban feature for the whole area of the stadium – Figure 12. The roof will be visible from high-rise buildings of Singapore downtown and from aerial views. The location of the Sports Hub close to the Singapore International Airport highlights the importance of the roof and its material assembly. Therefore the roof design considered visual consistency of the moving panels with the fixed roof in open and closed position. The panels match truss pattern on the fixed roof in open position – Figure 13. The artificial lighting features are inevitable part of the structure and support the continuity of the dome articulation. The pattern of the moving roof panels is formed by ETFE pillows that emphasise lightness of the panels. The stadium cladding has to meet environmental criteria and therefore the team use layered cushions with fritted surfaces. This solution provides a high degree of transparency for optimal daylight penetration and stop direct sun light entering the interior of the stadium.

The roof design is constrained by several performance criteria that came from usability such as requirement on operation of the both halves in the same time whilst the stadium is in use and when it is raining. The extreme weather condition for use is maximum speed of 13 m/s, maximum air
Figure 14. Part of the roof structure with connection to the louvered areas.

Figure 15. Detail of the louvers and fixed roof connection
temperature of +45°C and maximum humidity 95%. This was achieved with maximum opening and closing time 20 minutes.

8. Louvred Area

The careful modulation of the massing away from the waterfront ensures that experience at the water’s edge is about being in the landscape of the Gardens by the Bay. The building massing is also carefully designed to ensure a harmonious relationship with the existing SIS. The main circulation level for the National Stadium, the Sports Promenade level, is one level above natural ground, in order to avoid lowering the main stadium arena into the water table. It also has the advantage of being on the same level as the existing SIS circulation level. This level is formed between the National Stadium and the SIS with retail at ground level and garden terraces at the first floor level that overlooks Kallang Basin and the city beyond.

The promenade is a sheltered public space with easy access for general public. The external concourse is shaded by a system of overlapping louvers made of stretched PTFE fabric (Figure 14, Figure 15). This material is chosen for its properties such as translucency and durability. The woven fabric with coating is stretched on a tubular supporting steel structure attached to the

Figure 16. The parametric model for the optimisation of the louvers. The image shows two overlapped images of two extreme conditions for the louvers positions.
main arching trusses of the fixed roof and hanged from the interceptor truss. The hangers are in radial distribution along the concourse. Horizontal arrangement of the louvers has to satisfy several conditions: minimal overlap angle is 30 degrees for convenient flow of rain water, shading the space below the louvers, least interrupted view out of the stadium from concourses on levels 4, 5, 6, 7 and minimal surface area of the fabric.

The framing structure is guided by two set out surfaces of the dome – sphere and torus. The lower louver matches horizontal level of the floor at level 4 and the overlap angle was measured at the extremities given by irregular shape of the dome surfaces. The horizontal section of the torus is a curve with unequal distance from the circle which is a result of intersection of horizontal plane and the set out sphere. Therefore the overlap angle is measured at positions further away from the bowl short axis. The balance of the overlap angle, shaded are on the promenade and maximum view angle was found through optimisation method of genetic algorithm. This novel approach to design helped to decide the best position of the louvers. The parametric software with its ability for rapid change tested few hundreds of options and together with lighting analysis package Radiance gave answer to designers’ task. The separate model of the louvered area of the roof was modelled in parametric package Generative Components (Figure 16) and subsequently used for assessment driven by optimisation algorithm. The customised scripts were written by the author to connect different software together. The final result was achieved through

▼ Figure 17. The surface parametric model of the stadium roof
automation and ability of computer to give objective results. Although the changes seemed to be very subtle the impact on system of 14 louvers 350m long and about 5m wide was large. The total area of the fabric is 16 785m². The described approach to design could not be possible without use of computers and advanced complex algorithms. However the final decision was taken by the team of architects that assessed the form and its visual impact on inspection of virtual model and rendered images.

9. Conclusion

The roof of the National Stadium would not be possible to design without extensive use of computers and programmes allowing for associative design. The design starts from the basic principles and requirements on the seating bowl. The custom made program based on CAD software Microstation helped to design the best geometry of tiers that gave initial input to the form of the roof. The roof model was developed in software Digital Project and features a capacity for nesting of geometrical entities while maintaining its relationships (Figure 17). Studies of cladding that were executed in other software packages (Rhinoceros and Generative Components) were also implemented. The digital design of the roof addresses well options for assembly of the structural and cladding components [6].

Combining software is seen as the best approach for the roof design starting from initial digital sketches and structural form-finding and continued to detail design of optimised louvers. The digital design of the roof was not generative from its first principle but automation and objective form evaluation played significant role. The fabrication techniques will also influence the parametric model and considerably modify work flow of the later stages during the final design stage. With modern CNC manufacturing techniques and novel joint design the intricate parts of the roof can be built and inform the architectural design [4, 7].

The roof is not only a sheltering element preventing spectators from weather conditions but it helps to modulate environment inside the stadium. The complexity is increased by quality and performance of materials. The established theoretical range of temperature and humidity inside the stadium has to be achieved through a threshold of material system of the roof. The roof with its differentiated parts could be then considered as an envelope modulating the microclimate of the building [9].

Parametric modelling was the means of representing problem description as it developed. The design phases could not be strictly categorised. It offers an alternative to geometric constraints-based form generation [1] which is known for example from several projects of the UK office of Foster + Partners [9]. However the dome design features also performance-driven form generation especially from structural and environmental point of view. The combination of both approaches where the first is predominant led to elegant large scale structure.
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References


