

PARAMETRIC DEFINITION OF LANSDOWNE ROAD STADIUM

Paul SHEPHERD
Research Fellow
University of Bath
Bath, UK

Roly HUDSON
Researcher
University of Bath
Bath, UK

Summary

This case-study focuses on the new Irish National Stadium being constructed on the site of the historic Lansdowne Road Stadium in Dublin, Ireland. Due to the complex free-form nature of the architecture and the highly constrained urban setting, a parametric approach has been adopted. Early collaboration between the architects (HOK Sport) and the engineers (Buro Happold) resulted in a single parametric model being developed which was capable of generating both a complex geometric form and an innovative structural solution. The parametric modelling environment used was Bentley's Generative Components, and it was customised to link directly with a structural analysis package and to carry out panelisation studies. This allowed a fully parametric design process to be implemented, from architectural design, through structural analysis and optimisation, to manufacturing and construction of the façade. This documentation of the project provides insight into the implications of a parametrically enabled and integrated collaboration between architect and engineer on a complex large scale project.

Keywords: Parametric Design, Free-Form, Complex Geometry, Generative Components, Stadium, Collaboration.

1. Introduction

This paper documents the collaborative process of detailed design development and production of construction documentation for the new Irish National Stadium on Lansdowne Road in Dublin (see Fig.1). The collaboration between architects HOK Sport and structural engineers Buro Happold was enhanced through the use of a shared parametric model used for development and definition of both roof structure and cladding envelope.

The stadium site was highly constrained, with a tight boundary to the north and south formed by low rise residential buildings. These dictated rights-to-light planning restrictions, chamfering the possible development volume at the north end, and air traffic control regulations limited the overall height of the stadium to 50m. Expansion to the west was limited by the retained rail link and to the east by the grounds of a local rugby club. Inside the stadium resisting these external forces was a requirement for a seating capacity of 50,000. Exhaustive daylight studies defined the position of the inner roof edge to provide adequate natural light to ensure a healthy grass pitch growth.

The design submitted for planning approval proposed a form resulting from a combination of pressures from all these constraints. Although not initiated in a parametric way, the underlying geometric considerations for the early design were rule driven.

As the project entered the design development phase, the architects anticipated changes and adjustments to the constraints and therefore sought to use an integrated technology that could easily accommodate and communicate variation between the architects and engineers. This suggested a parametric approach with a shared initial setting out of geometry. The chosen platform was Bentley Systems' Generative Components (GC) [1]. The architects wished to retain control of the external geometry while the engineers would design the structural system to support this. A hypothetical boundary surface was discussed that separated the remit of engineering responsibility from that of the architect. The geometry of this interface was controlled by the architects and then passed to the engineers. This would allow the external geometry to be manipulated, these changes issued to the engineers, and then the structural geometry and corresponding structural analysis would automatically update.

A parametric approach meant that the geometrical configuration of the stadium could be numerically controlled, removing the need to manually edit and rebuild geometry when a change occurred. Popularity in the use of parametric systems in architectural design is increasing and results of use have been published [2], [3], & [4]. Potentially this technology means that design change is easier as it is less time consuming and therefore more solutions can be explored and evaluated. The working method documented here uses parametric technology to define building geometry and to form a dynamic cross-disciplinary link between architectural and structural design at the detailed design phase of a complex project.



Fig. 1 Aerial view of proposed stadium on Lansdowne Road site

2. Architecture

2.1 Model Structure Overview

Architectural modelling of the stadium geometry consisted of three key components. Numerical parameters, static geometry files, and a Generative Component script file. The parameters, or numeric data, were stored in an Excel spreadsheet, and were read into GC as the script file was played. Static geometry was also referenced in from CAD files. From this initial configuration and further instructions defined in the script file, a graphical control system was constructed which defined the configuration of the stadium geometry. This model structure provided a means for integrating various specialist skills of the stadium design team. The cladding team responsible for detail design and construction of the stadium envelope could manipulate parameters in the spreadsheet to alter geometry and extract two dimensional drawings for use in architectural plans, sections and elevations. A radial structural grid was referenced into the model which could be edited in static CAD packages and recombined with the parametric model. A specialist seating bowl design team provided both the back-of-seating-bowl curve, which was statically referenced into the model, and corresponding vertical offsets, which were passed into the model as numeric parameters via the spreadsheet. This package could then be issued to the engineers and the structural geometry constructed.

2.2 Geometric Method

The method of geometric definition consisted of an array of radial vertical planes defining the locations of the tertiary members of the roof structure. On each of these planes a sectional curve was defined (see Fig.2). This curve represented the interface between the architectural and structural design. Outside the section curve all work was the responsibility of the architects and inside the curve responsibility fell to the engineers.

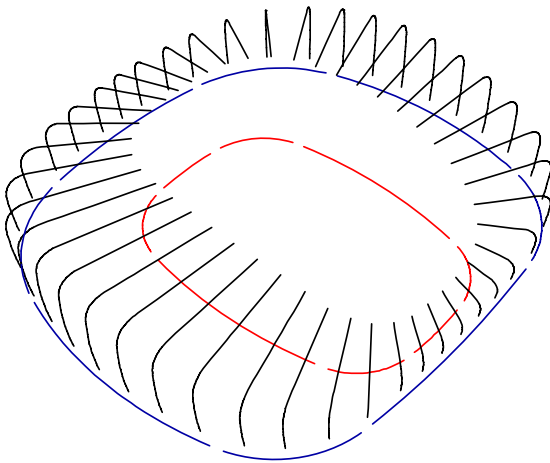


Fig. 2 Radial array of sectional curves

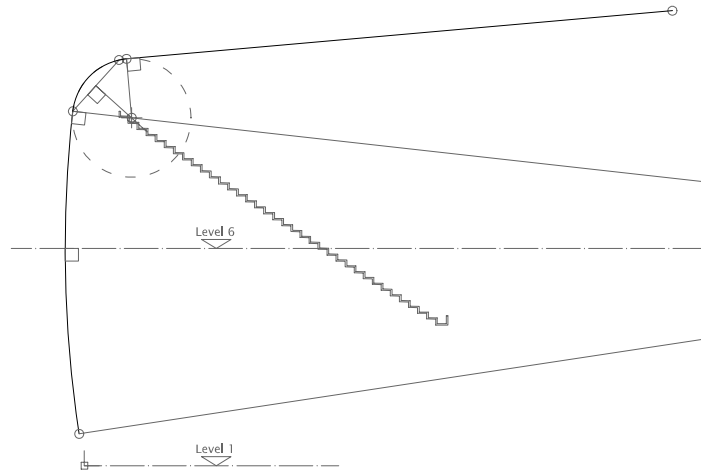


Fig. 3 Typical sectional curves

2.2.1 Tangential Arc Footprint

Eight parametrically controlled tangential arcs defined the footprint for the stadium, see blue curves on Fig. 2. A second set of tangential arcs defined the plan position of the inner roof edge or drip line, see red curves on Fig. 2. The intersection of the footprint and radial structural grid determined the origin of the sectional planes.

2.2.2 Sectional Definition

Each section consisted of three basic geometric objects, two arcs and a straight line, all of which were planar and met each other tangentially (Fig. 3). The configuration of each section was defined by three pairs of horizontal and vertical components. Three planar control curves mapped the vertical positions of the drip line, back of upper tier of seating bowl and edge of section above ground level. Horizontal components were defined by the intersection points of the radial grid with the drip line, seating bowl curve and stadium footprint. A further parameter defined a minimum vertical distance between the back of the seating bowl and the sectional curve ensuring adequate space for structural depth and headroom for a spectator in the last seating row. Given these six components it was possible to locate the centre, start and end position of each arc and the start and end of the line.

2.2.3 Geometric Control

An initial parameter set for the stadium was taken from the static model used for the planning submission. The key geometry (drip line, top of seating bowl curve and lower edge curve) was extracted and referenced into a GC model. Planes corresponding to the radial structural grid were constructed to intersect with the extracted geometry and used to define the initial set of vertical components. These values were stored in the parameter spreadsheet and used to construct the control curves for the driver geometry. These planar control curves mapped vertical variation clockwise from the north around the stadium (Fig.4). Such a control mechanism allowed sampling for a vertical component at any point around the stadium. This meant that the initial set of sectional curves corresponding to the tertiary roof structure could be further sub-divided in order to produce a secondary structural system for the support of cladding panels.

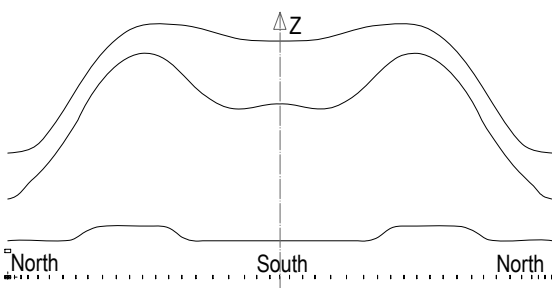


Fig. 4 Control curves

Existing footprint and drip line curves in plan were examined and a set of relational rules were determined for defining them as a composite curve consisting of eight tangential arcs. Numeric values relating to arc radii and centres from existing geometry were also used to configure initial parameter values.

At a later stage a further control curve was added to provide a means of increasing the radius of the filleting arc of Fig. 3. This added a degree of aesthetic control whereby the sectional curve could be made to appear less angular.

2.2.4 Two Dimensional Output

Built into the model are two mechanisms for extracting two-dimensional drawing data. These enable sections to be created corresponding to an orthogonal grid relating to the seating bowl structure and the extents of floor plates. In order to extract these, a surface is created by lofting through the section curves. A series of vertical planes are defined using the seating bowl grid and horizontal planes at each floor level. Two-dimensional curves at the intersection of the surface and planes can be extracted and stored in unique drawing files which were then referenced into the two-dimensional architectural drawings.

3. Structure

Since the architectural model developed above had a certain amount of design intent embedded within, and was also likely to go through a number of iterations as this design developed, it was decided that the structural model developed by the engineers would also be parametric, and that it would use the architectural parametric model as a starting point.

3.1 General Structural Layout

In order to support the roof without the need for columns being placed on the pitch or amongst the spectators, a long-span structural system was required which could transfer the loads back to the columns arranged around the outside of the seating bowl. The development of the structural solution involved a complex and technical design development, the details of which are outside the scope of this paper. The resulting scheme is made from a hierarchical steel truss system (see Fig. 5), comprising a primary horseshoe shaped truss (red inner ring), with full-depth radially aligned secondary trusses (green short, radial diagonals) between this and an outer circumferential truss (pink outer rings). Smaller tertiary trusses (blue radial lines) also span radially from columns around the outside of the bowl (black circles) and cantilever inside the primary horseshoe to extend the covered area of the roof.

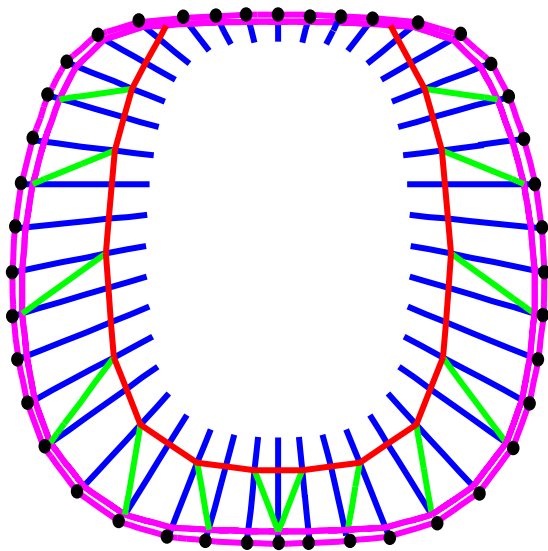


Fig. 5 Plan view of structural hierarchy

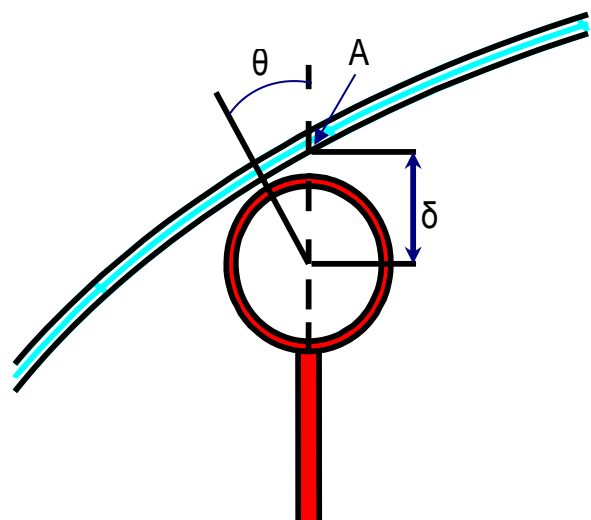


Fig. 6 Primary truss top chord offset under surface

Each of these trusses is made from a top and bottom chord with some type of lacing linking the two (generally N-bracing). As well as the surface and tubular model required to produce renders and for clash-detection, the engineers required a centre-line model of the truss elements for modelling in Finite Element Analysis software. This was created parametrically, for example for the primary truss as can be seen in Fig. 6, by projecting the horizontal position of the primary truss up to the surface (point A) and then dropping down by the radius of the top chord divided by the cosine of the angle that the surface makes with the vertical (θ). This point is then used to generate the chord geometry and by definition ensures the top chord does not poke through the surface. An additional offset was also introduced to allow for the surface-supporting structural build-up and tolerances.

3.2 Use of Real Parameters to Define Structure

As with the architectural constraints, a key advantage of taking a parametric approach to the definition of the structural components is that real constraints can be assigned as parameters and used to ensure that the resulting structure is compliant with these rules by definition.

3.2.1 Sightlines

Much care was taken to assess the view quality from every seat in the stadium to ensure the view of the pitch was as good as possible and compliant with the design brief. Since sightlines clearly follow a straight-line path, and with the design requirement that a spectator should be able to see a point 18m above the centre-spot of the pitch, they lend themselves to being easily introduced as a constraint into the parametric model. In this case it is important that a spectator sitting on the back row of seats can still see properly without having their view obscured by the bottom chord of the primary truss (see Fig. 7). However, for structural efficiency it was desirable that the primary truss be as deep as possible. Therefore, the vertical position of the centre-line of the bottom chord was defined to be exactly a chord's radius above the corresponding sightline, thereby giving maximum structural depth whilst maintaining a clear view of the pitch.

3.2.2 Bending Moments & Transportation

The shape of the bottom chord of the tertiary trusses was chosen to be based on a circular arc for aesthetic reasons, but faceted between lacing bays to aid constructability. Off-site assembly was desired to minimise cost, so each truss was limited to a maximum depth of 4.4m to allow for transportation to site. The point at which the bottom chord's arc achieved this maximum depth was derived parametrically by taking into account the bending moment diagram for a uniformly loaded cantilever with back-span where the triangular outer truss was assumed to provide rotational restraint. This allowed each individual truss to have its maximum depth exactly where it was needed, thereby resulting in an efficient design (as in Fig. 8).

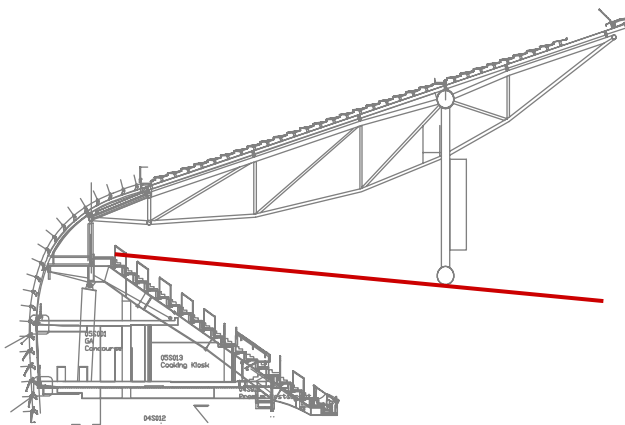


Fig. 7 Primary truss bottom chord avoids sightline

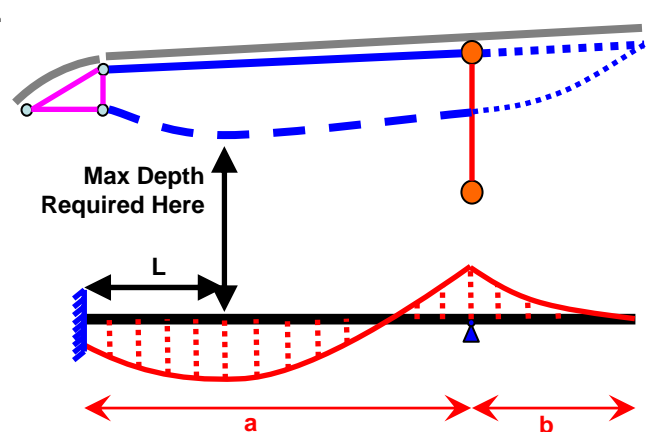


Fig. 8 Tertiary truss bottom chord follows bending moment

4. Analysis

One of the especially innovative aspects of this project was the inclusion of the engineering analysis process into the parametric workflow. The Generative Components (GC) system allows access to much of its functionality through an interface with Microsoft's Visual C# programming language. An export routine was written in C# and was embedded within the GC environment which took the parametric model and created a data file for the structural engineers' chosen analysis software Robot Millennium.

4.1 Section Sizes & Boundary Conditions

There was no available interoperability scheme between the GC modelling system and engineering analysis tools, since GC deals only with geometry and does not have any sense of structural member dimensions. So traditional methods of

CAD information exchange allowed the import of geometrical information into the engineering analysis software but the user would then have had to manually apply material properties and structural section sizes to each member. Although there were some ways to speed this up, such as using CAD layers to group similar elements together, the manual intervention required for this stage of the design process went against the ethos of a parametric approach to the project.

The C# program was therefore pre-programmed to understand which section size was to be assumed for each element type, be it a truss chord, lacing member or bracing. These sections were initially estimated based on engineering assessment of the loading conditions and spans, but were refined as the design process progressed. Additionally, the model boundary conditions used to represent structural supports, and member releases to simulate connections and movement joints, were also embedded into the exported model to save manual model building time by the engineer.

4.2 Loading

By far the main benefits from developing an interface with the analysis software were seen through the automatic calculation and application of the loading information to the model. Loading was required to represent the force generated by the weight of the cladding system, and the snow and wind loads required by the building codes. The loading was to be applied to the top chord of the tertiary trusses as a line-load representing the effective width of each truss. Since each truss was organised radially around the structure, the effective width of the inner end was less than that of the outer end, so a trapezoidal line-load distribution was required (see red lines in Fig. 9). The complex nature of the doubly-curved geometry, which can only take advantage of the single line of symmetry through the middle of the stadium, and the fact that each chord was segmented into between three and eight bays along its length, resulted in 207 different triangular loads being calculated for each of 2 base load cases (perpendicular- and gravity-loads). Obviously, to calculate these loads by hand would be prohibitively time consuming, not to mention tedious and prone to error, so there would have been a reluctance to update the load calculations every time the model changed shape. However, since the parametric model understands the relationship between each tertiary truss and its neighbour, the loading calculation could be performed inside the C# program and exported along with the geometrical information straight into the analysis software. At the same time the 31 different wind coefficients resulting from wind-tunnel testing were also combined to generate the entire set of 51 load-cases ready for analysis.

The result was a fully automated parametric system capable of modelling the entire stadium roof geometry from architect-driven conceptual principles, through structural geometry layout and out to engineering design software ready for analysis, without any need for manual intervention. This helped the design team to work efficiently and develop a highly optimal solution, maintaining compliance with a number of design constraints along the way with no extra effort.

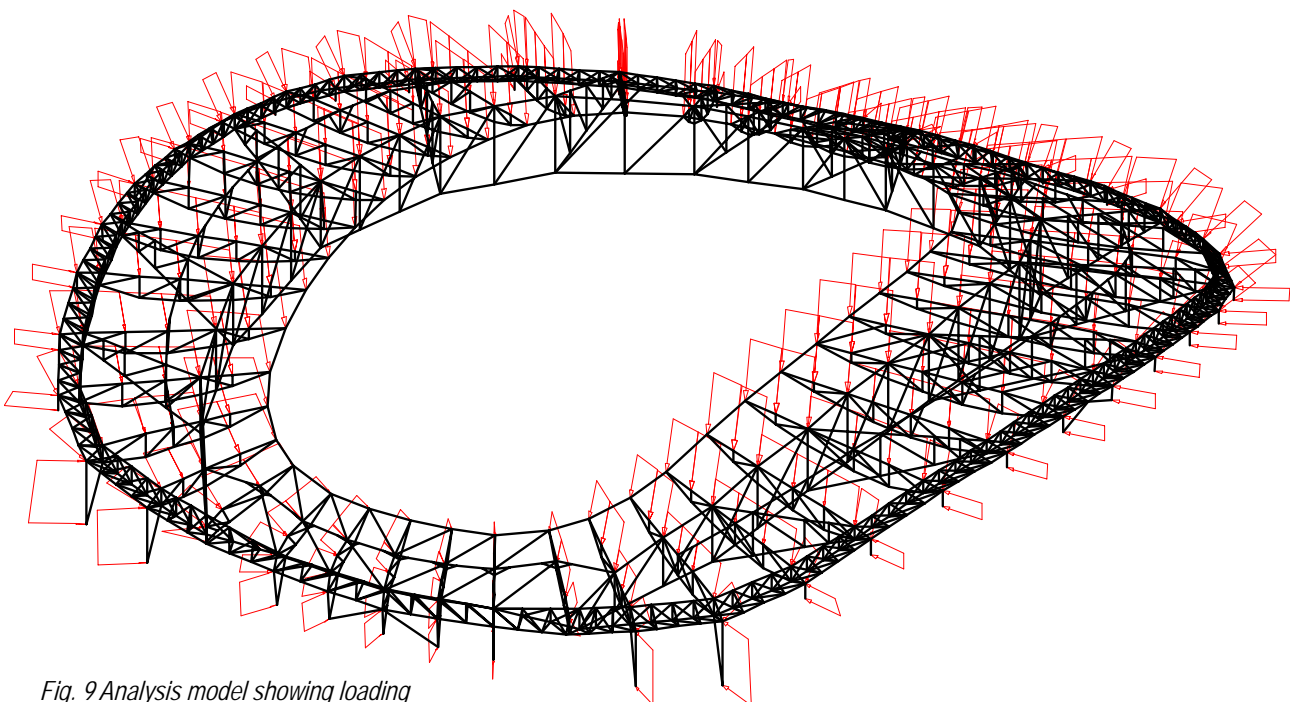


Fig. 9 Analysis model showing loading

5. Cladding

One of the key functions of the architectural model was the ability to create additional sectional curves between each bay of the tertiary roof structure. This allowed a secondary structural system for the support of cladding panels to be defined. The number of sub-bays was defined by a maximum panel length specified by the panel manufacturer.

5.1 Initial Studies

Variation in the length of sectional curves and a desire to use whole panels of standardised widths resulted in arrays of panels with ragged ends. Early studies explored various setting-out points and relative visual impact was assessed. Use of planar and twisted panels was assessed from both a construction perspective and in terms of visual impact. User defined tools were constructed and tested, which graphically illustrated drainage directions across panels and flagged panels that exceeded a maximum out of plane dimension, as defined by manufacturer's specification for the chosen material (see Fig.10).

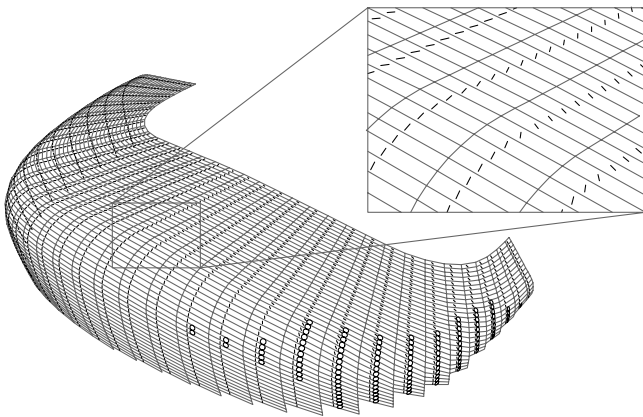


Fig. 10 Study showing runoff and panels exceeding maximum twist

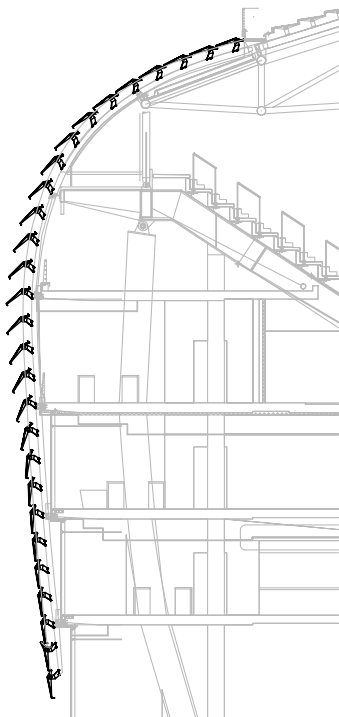


Fig. 11 Panel section

5.2 Cladding Geometry Method

The stadium skin was divided into two distinct zones separated by a gutter running around the roof edge truss. Below this divide, the façade consisted of a rain screen system (Fig. 11), and above the divide a sealed system covered the roof. Typically the cladding system consists of a folded polycarbonate profile panel of equal width but varying length fixed to a standardised bracket system with two axes of rotational freedom (Fig. 12). These axes of freedom allow the planar panels to follow the stadium geometry. Panels were detailed with a flexible gasket to allow tolerance as they overlapped the panel below. Each panel was fixed to a bar that was supported by the main brackets. For the façade this provided a third axis of rotation allowing panels to be rotated in to any position between 0° (closed) and 90° (open). Rotation angles for this third axis were defined based on data from mechanical engineers to ensure adequate air intake and exhaust volume for air handling units. These open units were gradually incorporated into the façade by feathering the rotational angles of the surrounding panels. The brackets for the roof zone were detailed to support a gutter that ran along the sectional curve.

The two bracket rotation angles and a linear dimension between panel support points were mapped to spreadsheets corresponding to unfolded elevations of the façade. These data sheets were issued to the cladding contractor as part of the construction documentation.

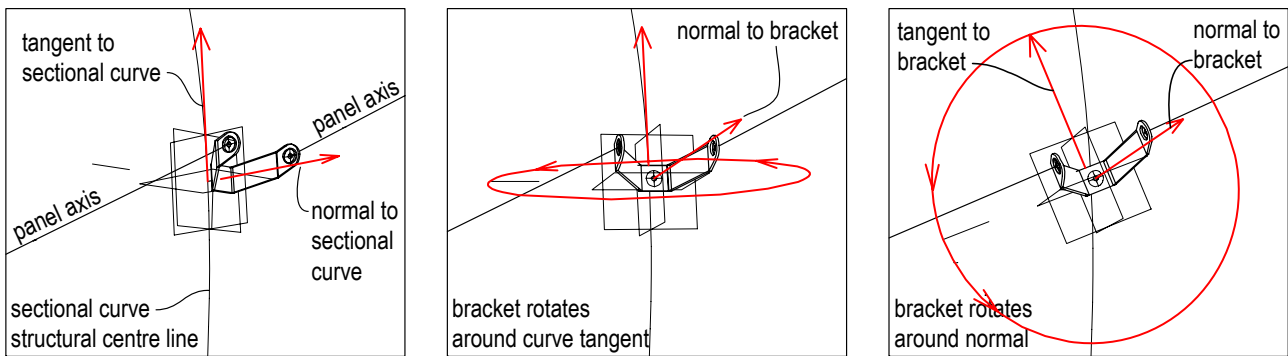


Fig 12 Panel bracket

Once the panel plane was found, a place-holder polygon could be constructed. This provided input for various components of panel assembly allowing different construction configurations to be tested and final three-dimensional models to be produced for visualisation and extraction of two dimensional stadium elevations (Figs. 13 & 14).

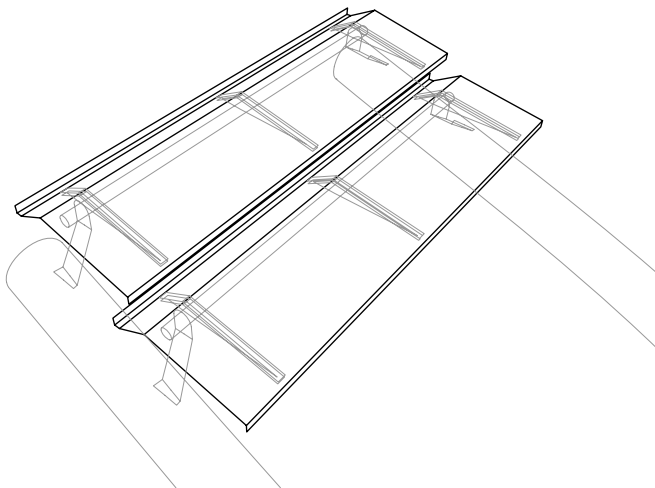


Fig. 13 Panel assembly

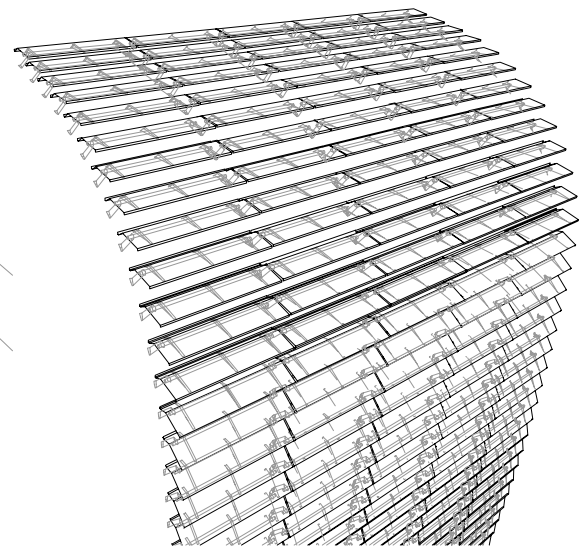


Fig. 14 Panel assembly over five bays

6. Conclusions and Lessons Learned

In general, the collaboration between architects and engineers worked very well. At an initial meeting of both parties, a division of responsibilities was agreed. It was also sensibly decided to freeze the version of software being used and not keep up to date with patches and upgrades, so that both parties could be sure they were working with the same program and what one would see, so would the other. This gave a firm base on which to build and an unambiguous point of hand-over from architecture to engineering. More specific conclusions are discussed below.

6.1 Collaboration

Since the architect's model was used as a starting point for the engineer, this sometimes caused problems when the engineering consequences of a change to the architectural model were not fully understood. For example, due to a change in the way the architectural model was described, at one point the composite curves used to describe the radial sections of the roof had their orientation changed so that instead of having their starting point at the outside of the bowl near the last row of seating and ending on the inside towards the pitch, they became reversed. Geometrically they described exactly the same shape, but their parameterisation was now different. Therefore, since the engineering model

had assumed the initial orientation would not change, and built on that assumption to construct the rest of the model, the system no longer worked. Once the cause was discovered it could be quickly be rectified, either by the architect ensuring that the radial lines once again went from outside to inside, or by the engineer re-working the structure based on the new, opposite assumption. However, problems of this sort are often difficult to understand, since the geometry handed over looks exactly the same, and so the resulting time required to deal with such problems is quite long. It was therefore agreed that all geometry descriptions would maintain their orientation if possible, and if not, the fact that they had changed would be flagged up during hand-over. Similar problems arose with changes in entity naming conventions and the way in which certain arrays of elements were ordered. So a clear understanding by the first party (in this case the architect) through regular briefings, of how the second party (the engineer) is building their model and what assumptions this makes, would be an important step in the design process.

6.2 Design Opportunities

The development of the cladding system illustrates some of the potential design benefits of using a parametric system. Many initial solutions were rapidly explored and evaluated in terms of both aesthetic merit and simplicity of construction, quickly discarding some of the many options. This also allowed the architect to fully develop a detailed design which could be directly translated into complex production and set-out information. This ensured that the design intent of the system could be directly shared with the cladding contractor, which also made costing and budget reviews more precise.

Earlier implementation of the parametric system, during the planning design phase for example, may have added further opportunities to explore and refine the overall stadium design in the same way as the cladding design demonstrates. When combined with a period of testing the system on a smaller initial data set, this may have also given the engineers and architects an opportunity to refine the structure of the model and information sharing mechanism.

6.3 Workflow

Another series of issues arose in the implementation of such a specialist technology into a traditional design team and its use on a real live project. On a traditional construction project, the team consists of a number of architects, engineers and CAD modellers, who can work in parallel and adapt to meet specific project deadlines. Since the technology used on this project was relatively new, it fell to the single Parametric Modeller in each of the design teams to build and operate the parametric model. Although other team members had a general understanding of the principles on which the model was constructed, they were not familiar with the specifics of model building within GC. This meant that the parametric modelling sometimes became a bottleneck in the design process. For example, since the engineers had also invested heavily in including the structural analysis model into the parametric software, when a geometry change was issued, or a new structural parameter needed to be implemented, they had to wait until the parametric model had been updated before structural member design could be performed or until traditional CAD drawings could be produced. This situation does not lend itself readily to a live project where deadlines and priorities can change on an almost daily basis. With traditional drawings, the implementation of CAD Standards means that other members of the team can take over and help out if one part of the modelling process begins to hold up others. However, the complex nature of parametric modelling and its relatively recent appearance in the design office mean that no such standards exist. So even with other suitably trained team members, any work-sharing would become difficult as any newcomer to the model would require a large amount of time to understand the way the model had been built up, or require a lot of the initial modeller's crucial time to have it explained.

It is suggested that consultants beginning to adopt parametric techniques think about how they might extend their internal CAD management standards to encompass some of the parametric modelling issues before embarking on live projects within the design team.

6.4 Conclusion

A parametric model of an entire sports stadium roof has been developed through close collaboration between architect and engineer. The model has been extended to integrate with structural analysis packages and cladding panel scheduling systems, allowing optimisation of often conflicting design variables. As with all new technologies, a number of issues have been raised and lessons have been learnt along the way, whereby the team would do things differently in the future. However, this project has been viewed as hugely successful, by both the architectural and engineering team, as a new way of describing and sharing complex information and working on developing that information in an iterative and collaborative way with minimal effort.

The project has succeeded in delivering a high-tech solution to a complex problem.

7. References

- [1] <http://www.bentley.com/en-US/Markets/Building/GenerativeComponents.htm>, Accessed 25/06/07
- [2] HESSELGREN L., CHARITOU R., DRITSAS S., "*The Bishopsgate Tower Case Study*", International Journal of Architectural Computing, Vol 5, No 1, January 2007 , pp. 62-81(20).
- [3] WHITEHEAD H., "*Laws of Form*", Architecture in the Digital Age - Design and Manufacturing, Branko Kolarevic Ed., Taylor & Francis, Abingdon, 2003.
- [4] FREIBERGER M., "*Perfect Buildings*", <http://plus.maths.org/issue42/features/foster/index.html>, Accessed 25/06/07.