Proceedings of the International Association for Shell and Spatial Structures (IASS)
Symposium 2015, Amsterdam
Future Visions
17 - 20 August 2015, Amsterdam, The Netherlands

On the Benefits of a Parametric Approach to Stadium Design

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Abstract

The design of a modern stadium is a complex process in which a vast number of, often conflicting, design requirements are negotiated and compromised. The wide variety of different professional disciplines involved and the large size of each discipline's team adds to this complexity. However for a design to be successful it needs to take into account this variety and ensure the final product is greater than the sum of its parts.

In this paper the author makes the case for taking a Parametric Modelling approach to stadium design, and demonstrates how the use of a single Parametric Model shared across the design team is particularly appropriate to tackling the challenges outlined above.

Drawing on the author's first-hand experience of designing realised stadium projects, including the Emirates Stadium and the Aviva Stadium, the suitability of Parametric Modelling, to address design issues such as geometry, structure, construction and spectator sightlines, will be demonstrated. The fast-changing nature of such technology will also be discussed, highlighting further opportunities to develop and improve stadium design in the future.

Keywords: Stadium, Parametric, Design, Modelling.

1. Introduction

When CAD software first began to replace pencil drawings as the primary means of design and communication in the building industry, it did exactly that. It replaced 2D paper drawings with 2D electronic drawings, but inherited the same creation process and workflow – it became Electronic Paper. And whilst this move presented ample benefits in terms of document storage, transmission and printing, it still represented any given design in a purely graphical form, with no encapsulation of the reasons behind design decisions or the relationships between different objects. As designs grew in complexity and size, this simple representation was no longer sufficient to support the building design and construction process and new approaches were needed.

Parametric Modelling represents objects in terms of their relationships with other objects, rather than in absolute terms (such as their position in space). During the building design process it is very often necessary to make a change in the size or position of an object such as a beam, column or floor-slab. But the underlying relationships between these objects does not change (a beam still joins the top of a column, a floor slab is still supported by a beam). By using computers to model buildings parametrically, a change in size or position can be made manually, and the computer can then automatically re-impose all the relative relationships in an instant. This makes the process of change effectively "free", and allows designs to be improved incrementally whereas previously it might not have been worth the investment of time. Once the relationship between a building's components is decided, a parametric modelling approach therefore allows decisions on the actual geometry of the building to be deferred, with temporary "place-holder" values used to progress the design and final accurate values chosen later.

Modern parametric modelling tools can also take over responsibility for choosing these values, "closing the loop" and allowing the optimisation of designs way beyond what would be possible through manual intervention alone [1].

Since modern stadium design is an extremely complex process, with many constraints and conflicts to be resolved, the ability to defer design decisions is a valuable tool. At the same time, the many rules and regulations which need to be complied with to ensure the safety and comfort of the building users lend themselves well to being incorporated directly into a parametric model.

This paper demonstrates, with the help of real case studies, how parametric modelling techniques are particularly suited to stadium design in terms of morphology, structure and function; identifying current benefits and future opportunities.

2. Morphology

Stadiums are very large and inevitably iconic buildings which make an impact on their surroundings, be they stand-alone entertainment venues (often the case with football stadiums) or part of a wider collection of sporting facilities (as with Olympic stadiums). They often, therefore, have complex external geometries involving doubly-curved facades. They also tend to be in high-value locations within cities where space is a premium and many different (often contradictory) design constraints vie for attention. Parametric modelling can therefore be of huge benefit to the designer, allowing the effects of experimentation and change to be fed back immediately and potential problems highlighted early on.

This was demonstrated with great success by architects Populous and engineers Buro Happold on the Aviva Stadium project at Lansdowne Road in Dublin, which is believed to be the first building designed using a shared parametric model between architects and engineers. The architects created a parametric model of the overall form of the stadium and also used it to design the façade, whilst the engineers used the same parametric model to design the roof structure.

2.1. Architectural Geometry

The Lansdowne Road site was particularly tightly constrained, sitting as it does in the heart of a residential part of Dublin Figure 1, sandwiched between a river and railway. In addition to the usual considerations of a typical large building project (budget, timescale, construction, etc.) the design of the Aviva Stadium also had to respect the following:

- Site Boundaries to the North and South
- Railway line to the West
- Existing rugby club to the East
- Culvert Sewer along the site boundary which could not be built on
- Height restrictions due to planning
- Light considerations to neighbouring properties
- Playing field pitch size regulations
- Seating numbers and view quality requirements

Figure 1: Aviva Stadium on a highly constrained site.

Taking these issues into consideration, many of which were interdependent, meant that a parametric modelling approach was vital to the success of the project. The ability to immediately visualise the effects of any changes was an important tool for the architects, and resulted in a building which was very close to the early design intent (see Figure 2).

Whilst the parametric design of the Aviva Stadium has been reported extensively in the literature ([2], [3] & [4]) it is worth considering the façade in particular as an exemplar of the benefits of parametric modelling to stadium design.

Figure 2: Aviva Stadium roof - computer render (left) and photo (right)

2.2. Façade

The façade of the Aviva Stadium is comprised of horizontal louvres running in vertical strips from a gutter-line up on the roof of the stadium down to the concourse at floor level below (as shown in Figure 3). The purpose of the façade is to act as a rain-screen, preventing wind-driven rain from reaching pedestrians on the internal walkways, but at the same time allowing air to enter where needed by the large-scale servicing machinery inside.

Figure 3: Aviva Stadium louvres transition from open (left) to closed (right).

The louvres therefore needed to be closed (rotated about their own axis so as to be nearly vertical) around walkway areas, but opened (rotated until nearly horizontal) adjacent to plant-rooms. Whilst the louvres were made from the same folded pieces of polycarbonate, the complex curved nature of the façade meant that each louvre needed to be a different length to span between its supporting mullions, and each mullion bracket met the louvre at a different angle. Since each louvre had a different position in relation to the walkways and plant-rooms, each also had an individual angle of rotation between open (90°) and closed (0°).

By extending the use of the parametric model to incorporate the façade, the individual lengths and angles of each louvre and mullion could be automatically extracted and sent to the façade contractor for fabrication. The rules and relationships of the lengths and angles were the same across the entire façade, only the actual values changed. Therefore a parametric model was the ideal way to create the smooth variation of the louvre geometry across the façade seen in Figure 3, without requiring unmanageable amounts of manual intervention. This resulted in an elegant aesthetic as well as excellent functionality, keeping visitors dry and the building services ventilated. Whilst a louvred façade is not necessarily a common feature of stadiums around the world, the desire to clad a doubly curved façade in similar panels is, and parametric modelling can help remove the need to manually generate thousands of similar panels, allowing detailed exploration of different design solutions (indeed the Aviva Stadium parametric model was initially used to investigate panel-repetition, drainage and twist of solid cladding strategies before a louvred system was chosen) and integrating with modern fabrication methods at the same time.

2.3. Discussion

The unprecedented sharing of a single parametric model across disciplines did present some challenges for the design team. The legislative framework in which the building was procured was not able to properly account for this sharing of responsibilities and an agreement had to be reached as to where the architectural responsibilities stopped and the structural engineers' responsibilities began. This raised an important point about how the contractual and legal aspects of building design are not keeping pace with the rapid developments in digital technology and the influences this has on the design process in practice.

Similarly, whilst detailed design information for each individual façade louvre panel and mullion could be automatically extracted from the parametric model, the façade contractors themselves were unable to use this information directly via digitally fabrication, and manual cutting and drilling techniques were employed. Since the Aviva Stadium was built (2010) digital fabrication tools have become much more widespread. But it may take some time before these techniques can be used as standard.

3. Structure

Since load-bearing columns are generally not compatible with the activities which go on inside a modern stadium (be it a sports field or concert venue), the structural design of a stadium roof tends to involve long-span steel trusses which must work very hard to support the weight of the roof and withstand the relevant snow and wind loads. Oversizing of the roof truss members is penalised two-fold, since it adds to the self-weight of the truss, which then requires more steel to support it. These large trusses are generally highly visible, both externally and from within the stadium and form a strong part of the stadiums aesthetic. So control and flexibility in the roof structure's geometry is crucial – something which parametric modelling can deliver.

3.1. Overall Structural Geometry

In the case of the Aviva Stadium, the deepest possible primary truss was needed in order to make the most of its structurally efficiency. However, it was important that the truss did not begin to encroach on the views of the spectators below (see Figure 4).

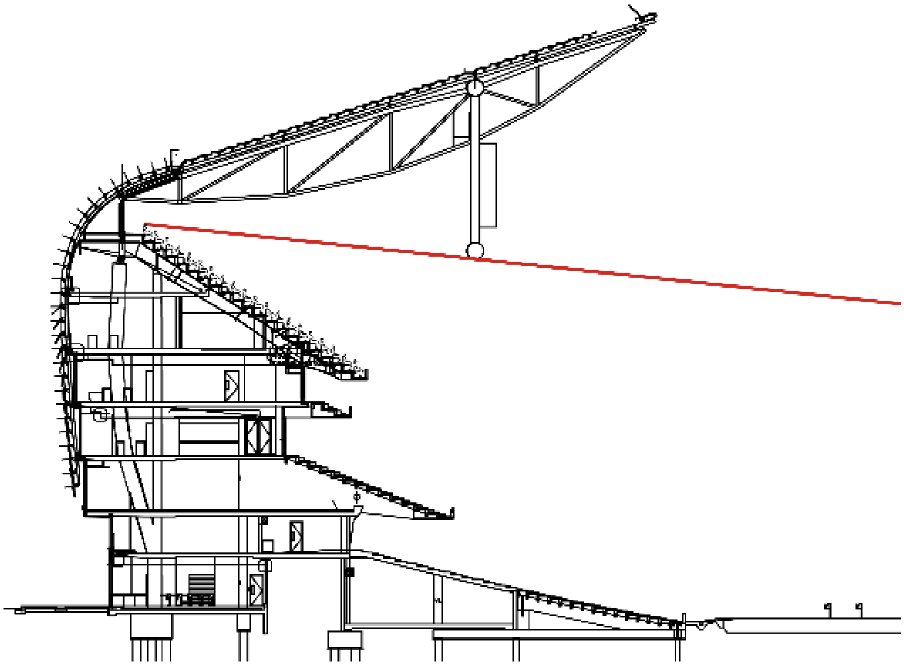

Figure 4: Aviva Stadium primary truss defined by sightline

The engineers' parametric model of the roof truss geometry was therefore defined relative to the sightline of the spectator on the row of seating furthest from the pitch, and ensured that such a spectator would be able to see 18m above the centre spot, thereby meeting the view-quality requirements and not spoiling their enjoyment by temporarily losing sight of a ball kicked high across the pitch. This one rule was automatically applied to every individual spectator (on the back row) thanks to the parametric modelling framework.

3.2. Element Design

On the design of the Emirates Stadium at Arsenal, London, the roof truss geometry was also parametrically defined and underwent intense non-linear structural analysis using non-matrix methods to assess its buckling capacity.

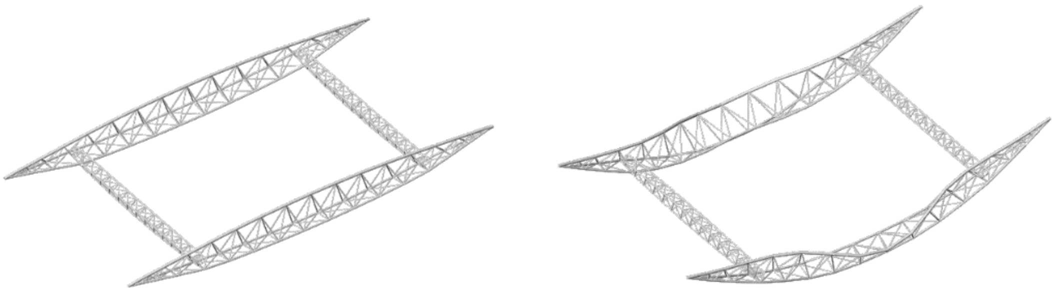

Figure 5: Emirates Stadium roof truss – undeflected (left) and buckled (right)

The truss has an overall triangular cross-section, with each chord curved independently and the discretisation of the truss and its lacing strategy also controlled parametrically. In this way, many different options had their performance assessed via non-linear buckling analysis and an efficient design solution found (see Figure 6).

Figure 6: Emirates Stadium roof truss

3.4. Structural Loading

The true power of parametric modelling for structural engineering was demonstrated on the Aviva Stadium project during the creation of the finite element analysis (FEA) model of the roof. A fully populated FEA model of the roof containing 3000 bar elements was automatically created from the shared parametric model, with all steel (CHS) cross sections and support conditions included. Each roof truss needed a distributed load applied along its top chord to represent the weight of the roof cladding, snow and wind. Since each structural bay was wider at the back than the front, this load should change in magnitude along the length of the truss (see Figure 7). And since each bay was a different width and span, each roof truss would have a unique loading pattern for each of the 23 basic load cases. Using conventional (CAD) modelling tools this would involve an impractical amount of work, and inevitably a conservative approach would be taken involving identifying the worst load case and applying the same load uniformly to each truss. Care would be needed to ensure that the loading was indeed conservative, since in some asymmetric wind cases, maximum magnitude load is not necessarily the most onerous case.

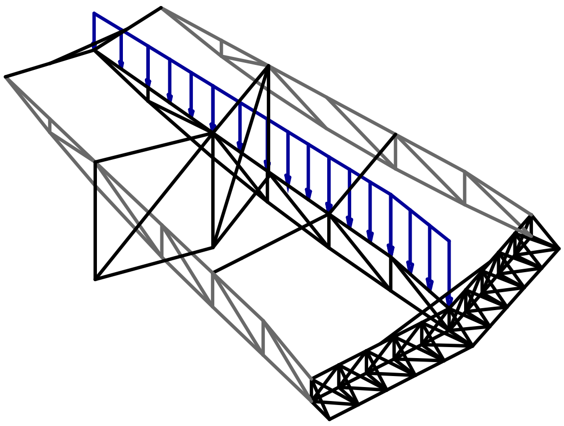

Figure 7: Aviva Stadium roof truss (grey) with loading (blue)

In contrast, using a parametric model to automatically generate the loads from a single set of rules allowed more representative loads to be applied with no extra work. And if the design geometry or structural layout changed, no extra work was required to update the FEA model and reproduce the design calculations. This is discussed in much more detail in [5].

3.5. Discussion

A parametric modelling approach to structural geometry and analysis is especially useful for the types of long-span non-prismatic trusses commonly seen in stadium roofs. Stadiums might require particular attention to seismic analysis and consideration of the temporary condition during construction. Retractable stadium roofs in particular might require dynamic analysis or analysis in various different geometric states. In such cases, a carefully constructed parametric model can help generate these various states with little extra effort. And if problems are identified during analysis, the models can be updated with new design decisions relatively easily. On the Aviva Stadium project the geometry of the stadium needed to be changed (walkways were widened) to improve emergency evacuation times one week before a major issue of drawings to the contractor. Thanks to the parametric model the new geometry was generated, a new FEA model extracted and analysed, and the structural engineering design re-checked within the week and the drawings were issued on time.

4. Function

Another time consuming task in the design of a modern stadium is that of assessing the architectural functioning of the stadium when occupied by people. Of particular concern in a stadium is the quality of the view of each of the 80,000+ seats.

4.1. View Quality

The view of a spectator can be obstructed by two main obstacles, the stadium structure itself (as shown in Figure 4) and the other spectators sat in front. The design of the seating bowl is therefore given careful consideration, and in practice the height of the steps of the seating bowl is determined by the desired view quality indicator, the "C-Value". This C-Value is the vertical distance (in mm) between a spectator's line of vision and the eye of the person in front, as indicated at the very right of Figure 8.

For a given C-Value "C" and tread width "T", the height of the step "N" of a seat a distance "D" horizontally and "R" vertically from a target view point (usually the touchline), is given by Eqn. 1.

$$N = \frac{(R+C)\times(D+T)}{D} - R \qquad (1)$$

This simple rule is easy to incorporate into a parametric model such that the seating geometry is generated for a given C-Value once the first spectator is placed in the first row. This was implemented in the Emirates Stadium project to allow an in-depth study of how the seating quality impacted on stadium capacity. Seats with better quality views take up more vertical space, leading to steeper raked seating. However planning constraints at the inner London site meant that having better view quality seats resulted in fewer rows of such seats before the height limit was reached. Therefore a compromise between view quality and seating capacity had to be negotiated, involving predictions of likely revenue from each quality of seat, and profiling of spectator demographics to derive the right proportions of different quality seating. The resulting design included a range of seating quality, from C120 in the executive and VIP areas, down to C60 seating for general admissions (still twice the best quality seating present in the client's previous stadium), as shown in Figure 9.

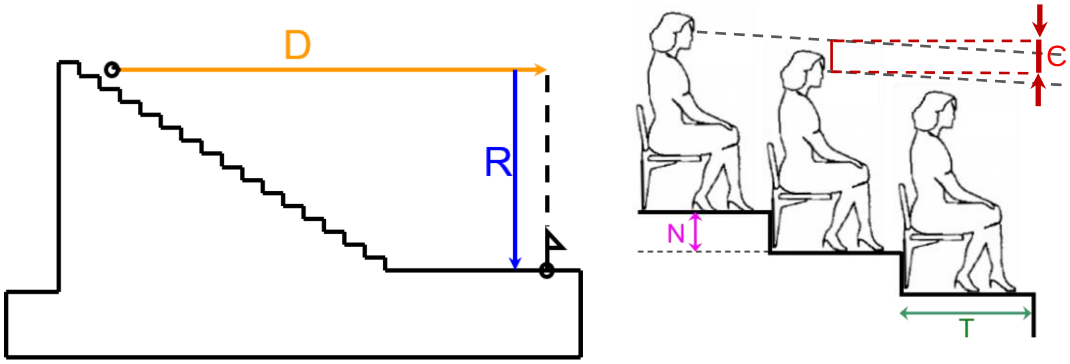

Figure 8: View quality is dependent on the position of the seat (left) and the seating geometry (right)

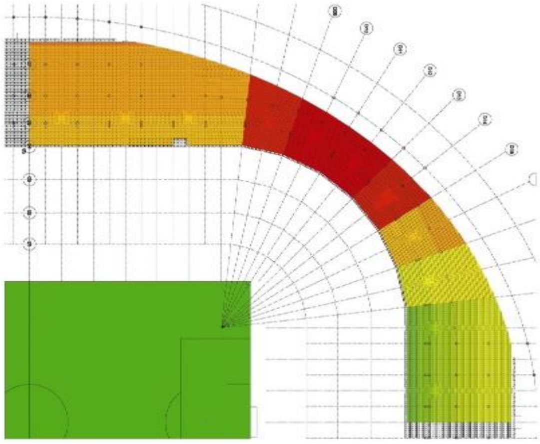

Figure 9: Emirates Stadium C-values optimised to maximise quality and revenue

4.2. Discussion

Parametric modelling can play an important role in the design of the functional aspects of stadiums such as view quality. View quality is more complicated than the basic 2D investigation carried out for the Emirates Stadium, and needs to be implemented in 3D, and including means-of-escape and disabled-access considerations, to fully realise its potential. Some progress has been made along these lines by others since ([7],[8]) and it is only a matter of time before such things make their way into commercial parametric modelling software.

Other areas of analysis into the function of a stadium which were considered during the stadium projects described above were the way the geometry of the stadium influenced grass growth on the pitch, the shadows that the roof cast onto the pitch during a match and the influence of the TV camera positions on their view of the pitch. All of these issues would benefit from a parametric approach in the same way. Similarly, closing the loop by allowing the computer to update the parameters to improve these aspects would result in a much more efficient design with little extra effort.

5. Future Development

The power of commonly available computer hardware is improving at a rapid rate [9]. And despite some who predict a slowdown [10] it is clear that the building industry still has a long way to go to take full advantage of this potential. A full 3D parametric model of an entire stadium, incorporating external skin, structure and internal functional spaces, and integrated with structural analysis and digital fabrication is perhaps still a long way off. And the legislative framework in which stadiums are procured perhaps has time to catch up. But the benefits of such a model would be immense, not only to the design team as a means of generating and improving a design, but also to the contractor who has to build it and the client who has to pay for it, manage and maintain it, and perhaps sell it or decommission it at the end of its life. Stadiums are large and complex buildings, and their design is driven by rules and constraints. They go through many design iterations and computational optimisation can make huge savings in terms of their large numbers of similar elements, be they structural, façade or seating. All this means that the future potential of parametric modelling for stadiums is enormous and the best is yet to come.

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