Aviva Stadium: A parametric success

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Abstract

The Aviva Stadium, Dublin, is the first stadium to be designed from start to finish using commercially available parametric modelling software. A single model in Bentley's Generative Components was shared between architects and engineers, which allowed the optimised design of form, structure and façade. The parametric software was extended where necessary to integrate with structural analysis and to automate fabrication. By reducing the overhead associated with design iterations, this approach allowed detailed exploration of options and early identification and resolution of potential problems. In this paper, the authors add to the body of scientific knowledge by describing in detail the methods which led to the construction of the Aviva Stadium. This paper is written in light of the completed building and provides information on the generation and control of the envelope geometry, development and analysis of structure and documentation for construction. Whilst these components have been discussed independently previously [1–4], here these aspects are drawn together for the first time and are presented alongside thoughts on the manufacturing and construction processes from the project architect.

1. INTRODUCTION

1.1. Project description

In May 2010 the new 50,000 seat Aviva Stadium at Lansdowne Road in Dublin was officially opened, celebrating its iconic form (Figure 1) and innovative design. The scheme design of the stadium was developed to be both responsive and empathetic to the surrounding neighbourhood. It has an organic translucent form, allowing the maximum amount of daylight into the seating tiers and onto the surrounding environment, whilst minimising the impact of the new stadium on existing buildings. The form of the exterior skin envelops both the roof structure and the façade structure, combining both elements into one controlling form. This concept emphasises the importance that the form of the building had in the design process, as it needed to accommodate all tolerances and technical requirements of both the façade and the roof elements into one three dimensional set-out model.

Whilst buildings have been designed using parametric modelling techniques in the past, the first being the Barcelona Fish [5] and arguably the most notable being the British Museum Great Court [6], such designs were carried out using bespoke software routines written and used by an isolated part of the design team be it architect (Barcelona Fish) or engineer (British Museum). By the time the design concepts for the Aviva Stadium were being formulated, a parametric approach to building modelling was just starting to become integrated into commercially available CAD products, allowing parametric models to be shared amongst team members and fully integrated into established design practices.

This paper describes the way in which the project architects Populous (formerly HOK Sport), and the structural engineers Buro Happold, were able to produce such a complex and visually stunning building by sharing a single parametric modelling framework which allowed rapid response to design changes and provided full coordination between teams.

► Figure 1: Photo of Aviva stadium in the final stages of construction.

1.2. Information workflow

Initial studies and concepts were undertaken using a combination of 3D programs. Firstly, using McNeel's Rhinoceros platform, 3D models were created using a set of tangential arcs aligned along the radial structural grids of the building. This early work allowed the architects to quickly explore the development and logic of the form's geometry. Once this construction logic had been tested around the building, the geometry of the model was rebuilt within Bentley's Generative Components (GC). It's important to note that at this stage the design focussed on the development of a setting-out geometry that corresponded to a structural grid arrayed around the building. All the architectural and structural elements would be related to this underlying geometry. The anticipation of a design evolution of the shape of the building through all these elements was paramount to the construction of the GC model. Thus certain variables and basic principles were established within the GC model, allowing control over the final form of the model to be maintained. This allowed the model to be parametric, having internally defined variables, but also constraining the geometry to certain grid-lines and limiting it to specific boundaries. For the architects, this was the most critical aspect of the parametric design since the finished construction geometry would be set-out directly from the parametric skin of the building.

Having established a 3D parametric model that formed the basis for the setting out of the façade and the roof structure, attention was then focused on the implementation of all other elements from this controlling shape. Through a close collaboration between the architects and the structural engineers (Buro Happold), the setting out principles by which the structural roof members would relate to the parametric skin were established. A framework was developed, by which the information could be exchanged between both parties, but with the architects ultimately driving the overall form and cladding of the building, and with the engineers driving the structural member sizing / positioning (Figure 2). To achieve this, a single GC script was produced to generate the set-out geometry, which referenced an external Excel spreadsheet containing the defining parameters. This set-out script was then used as the basis for design by both architects and engineers. Thus both parties could work simultaneously on the model in different offices, the engineers further developing the structural members by extending the original GC script file and the architects separately developing the original script to define the cladding layout. With the basis of both models being dependant on the input from the single Excel document the entire design of form, structure and cladding could ultimately be amended and refined by altering the parameters defined in Excel, meaning the inter-office co-ordination between the two disciplines relied on the transfer of a single Excel document.

Due to the geometric principle of the form defining both the façade skin and the roof structure, any amendment to the shape of the building at a lower level would have a knock on effect to the roof shape above. For this reason the parametric relationship and the combined use of GC across both offices allowed the architects to amend the form in response to certain criteria such as concourse width requirements, floor area ratios, or simply beautifying the shape, by amending the Excel document to reflect the desired change to the form and sending an updated Excel spreadsheet to the engineers. Thus the structural model defining all 3500 tons of structural steel could be re-calculated using an updated set of parameters to reflect changes in architectural requirements.

► Figure 2: Collaborative design process.
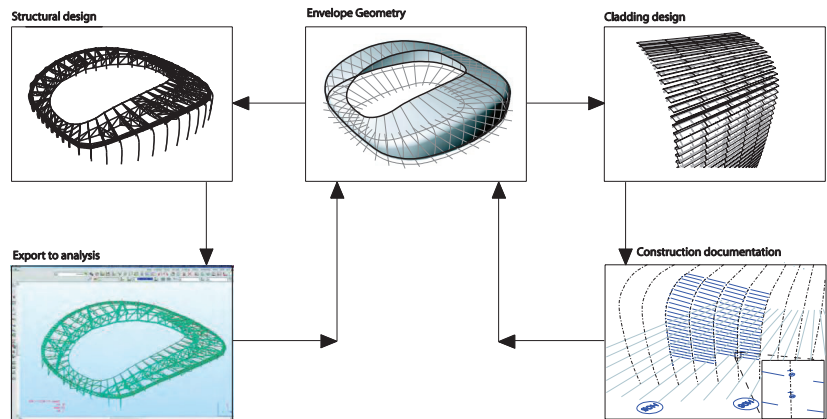
2. ENVELOPE GEOMETRY

Architectural modelling of the stadium envelope geometry consisted of three components; numerical parameters, static geometry files and a GC script file. The parameters, or numeric data, were stored in an Excel spreadsheet, and were read into GC as the script file was executed. Static geometry was also referenced in from CAD files. From this initial data and the rules defined in the script file, a graphical control system was constructed which defined the configuration of the stadium geometry.

The first step in the geometry construction sequence was to import the CAD file that defined a radial grid corresponding to the structure of the primary roof bays (Figure 3a). Eight parametrically controlled tangential arcs defined the footprint of the stadium (Figure 3b). The same system was used to define the inner edge of the roof (Figure 3c). The intersection of the footprint and the radial grid defined the origin of each sectional curve (Figure 3d). Each section comprised of two arcs and a straight line all meeting at tangents (Figure 3e). Vertical coordinates for each section were defined with three planar control curves

(Figure 3f). Horizontal coordinates were determined by the intersection of the radial grid and the footprint curve and the inner roof edge curve. Once each sectional curve was constructed, a surface could be lofted through the entire array (Figures 3g & 3h). When the radial roof bay grid was subdivided into mullion grid-lines, the continuous control curves allowed mullion sectional curves to be defined (Figure 3i).
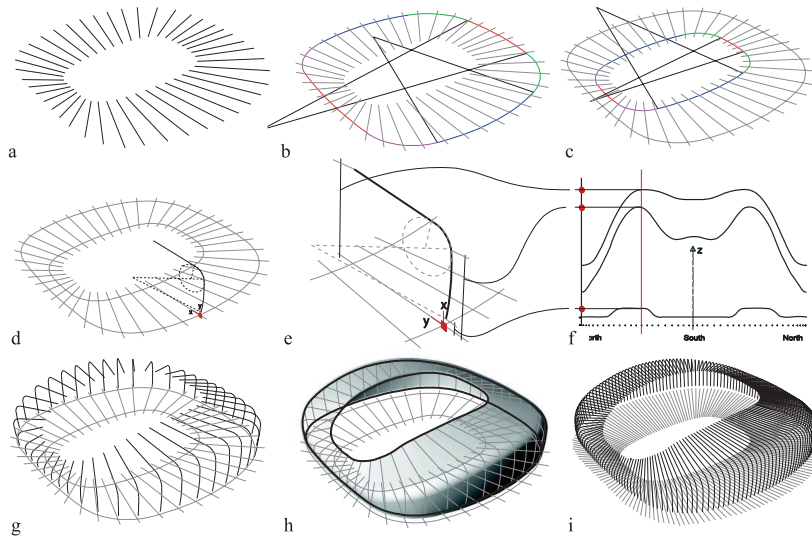
◄ Figure 3: Geometric definition of envelope.

Built into the model were two mechanisms for extracting two-dimensional drawing data. Using the lofted surface and an orthogonal grid that corresponded to the seating bowl, vertical sections could be extracted. Floor levels, defined in the spreadsheet, controlled horizontal planes which defined curves when intersected with the envelope surface. By offsetting these curves inwards, the extents of floor slabs could be defined. Once extracted, these sections and plans were saved in individual drawing files which could be referenced into Populous' design team's set of two-dimensional plans and sections, allowing co-ordination of internal fit-out with the three-dimensional form.
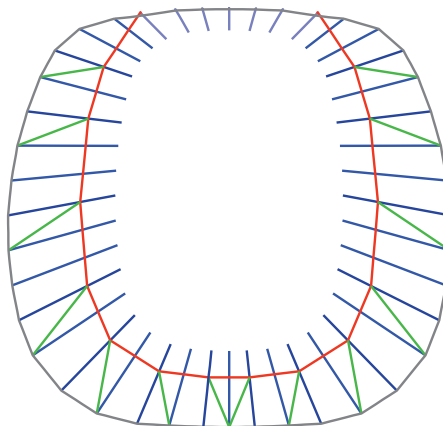
3. STRUCTURE

In parallel with the early studies on envelope geometry performed by the architects, various structural concepts for the roof truss were trialled by the structural engineering team using a simple parametric model based in Excel linked to the Robot Millennium (Robot) structural analysis package. Through these early studies, and the responsive dialog they allowed with the architects, the overall structural concept for the roof was formed. Once the architectural parametric model of the stadium envelope was complete,

the fact that a parametric approach had already been taken in these early studies by the structural engineering team meant that it was relatively simple to integrate the roof structure into the GC model.

3.1. Geometry

The primary structure to support the roof (shown in red on Figure 4) is a horseshoe-shaped steel truss. In order to be compatible with the architecture of the roof skin, the open end of the horseshoe is lower than the rest. The open end therefore rests on abutments and thrusts its load directly into the ground. The rest of the horseshoe is supported by large radial secondary trusses (green in Figure 4) that pick up the vertical load of the primary truss and transfer it back to columns around the outside of the bowl. Smaller, tertiary radial trusses (shown in blue on Figure 4) pick up the load of the roof between secondary trusses and span it onto the primary truss and an outer edge truss (grey in Figure 4) which runs around the outer edge of the roof.

▶ Figure 4: Schematic diagram of structural hierarchy.

The parametric model was used to ensure all truss top-chords were offset from the architecturally defined control surface by their section-size radius and a fixed dimension, ensuring there would be no clash between this supporting structure and any roof support structure or cladding. Apart from such inherent benefits of using GC in terms of coordination and ease of modification, the rule-based approach of the parametric model also allowed other practical considerations to be embedded within the design.

Similarly the tertiary trusses also gain strength from their structural depth, but increasing this depth also requires more steel and leads to a heavier, more expensive structure. Each truss requires more depth exactly where its bending moment is highest. Therefore a usual approach to optimising truss design is to change the depth of the truss along its length to follow the bending moment diagram. By assuming a simplistic model of

the tertiary trusses as propped cantilevers (cantilevering out from the outer edge truss which provides rotational restraint, and resting on the primary truss with little rotational restraint) an equation was derived for the level of bending moment at any point along the truss. This equation was then embedded within the parametric model, such that the bottom chord of each tertiary truss was individually shaped to have maximum depth at the point of maximum bending moment. Since each truss is a different length they had to be fabricated individually anyway, so the fact that each had a differently shaped bottom chord did not increase fabrication costs, and indeed resulted in less material being used as each was optimised for the task it had to perform.

By defining every steel member, including truss lacing and bracing members, the parametric model fully defined the roof supporting structure (Figure 5) and could be used to directly generate a structural analysis model.
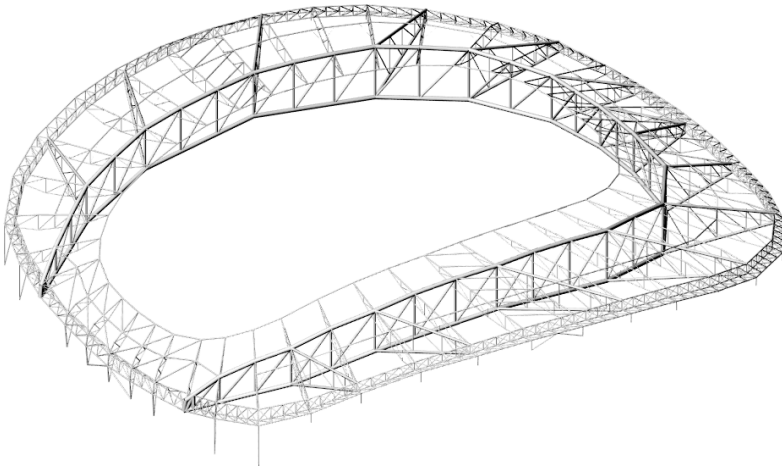
◄ Figure 5: Structural members output from parametric model.

◄ Figure 6: Photo of completed roof steelwork.

3.2. Analysis

The real benefits of taking a parametric approach to structural modelling were seen through the integration with structural analysis software. The GC parametric model was extended through its C# programming interface to export a structural analysis model ready for calculation. The structural engineers used Robot Millennium (Robot) for their design analysis. Whilst Robot is capable of importing the standard DXF files that GC can output, this method of file exchange only communicates geometric information and any additional information in the GC model is lost and needs to be manually re-input by the user. This breaks the parametric association and means that upstream changes in the design have significant time overheads in terms of rebuilding the analysis models. For the Aviva Stadium project, a special C# program was written within GC which exported data in Robot's native text file-format. This allowed the full intelligence of the parametric model to be shared with the structural analysis package and minimised human intervention through each design alteration. The most significant benefit of this approach was seen in the calculation of the loads on the structure. Wind design loads from wind-tunnel tests act over the surface of the structure and the exact shape of the geometry has a significant effect on the loads applied to each structural member, dependant on angle and effective-width. By incorporating the application of wind-loads into the parametric process, each of the 20 basic load cases and 70 load combinations could be automatically calculated and applied to each of the 3500 analysis elements.

Without structural analysis being included within the parametric model framework, fewer analyses would have been possible within the project programme and inevitably, conservative assumptions would have had to have been made which would have led to a less optimised and less efficient design. The extension of GC to bring structural analysis into the family of parametric modelling tools facilitated a more collaborative approach to design. The repercussions of architectural design decisions in terms of structural requirements could be quickly assessed by the engineering team and fed back to the architectural team. This allowed each discipline to respond quickly to the others requirements and a truly holistic design solution was achieved.

4. CLADDING DESIGN

The starting point for the cladding design was also the radial grid array of sections (Figure 3g) that define the envelope geometry. Further intermediate sections (Figure 3i) were required to define mullions to support the cladding between structural bays. Each structural bay was divided into three, four or five cladding-bays depending on the bay's structural lacing of the edge truss. The cladding system was designed as a rain screen consisting of inter-locking louvers (Figure 7). Panels were planar

and made from folded polycarbonate sheets; all panels used the same profile but varied in length. A lateral axis of rotation allowed panels to be fixed in a range of positions between open and closed (Figure 8). This allowed sections of the facade to be open to allow air intake and exhaust for air handling units positioned behind the facade within plant space plenums. The polycarbonate panel was fixed onto an axle along its own lateral axis. This axle was supported at either end by a bracket which was connected to a mullion. The brackets had two axes of rotation; the angles if which were defined by the positions of neighbouring panels (Figures 9 & 10).

In order to control the openness of panels on the facade a control strategy was developed that mapped the rotation (opening angle) of each panel from a cell in an Excel spreadsheet onto the facade. In this way an abstract elevation was visible in Excel that allowed the locations of air handling plenums to be specified on the facade. In these areas, panels would be open to allow air intake and exhaust. Surrounding these open areas, functions were written in Excel to feather the open angles back to a closed position, creating smooth transitions between the open and closed areas (Figure 11). Parametric modelling of the entire facade provided a means for checking that Populous' proposed cladding system would work correctly around the entire stadium envelope and also provided a high level of architectural control. The parametric model was also used to produce geometry files for three-dimensional visualisation both in computer generated graphics (Figure 7) and physical models (Figure 12).
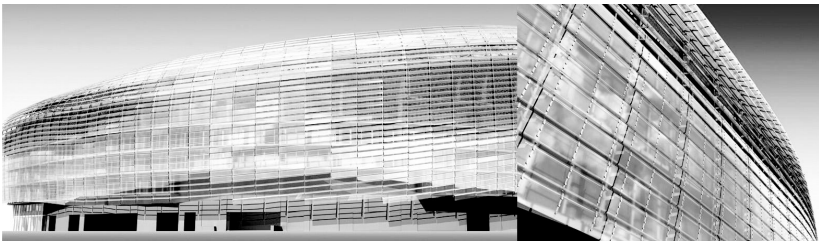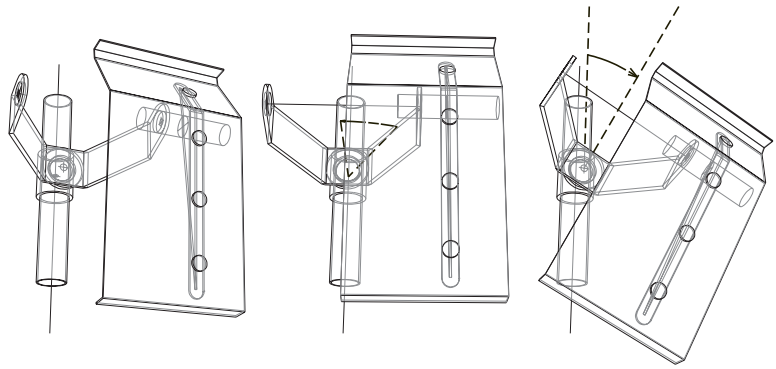

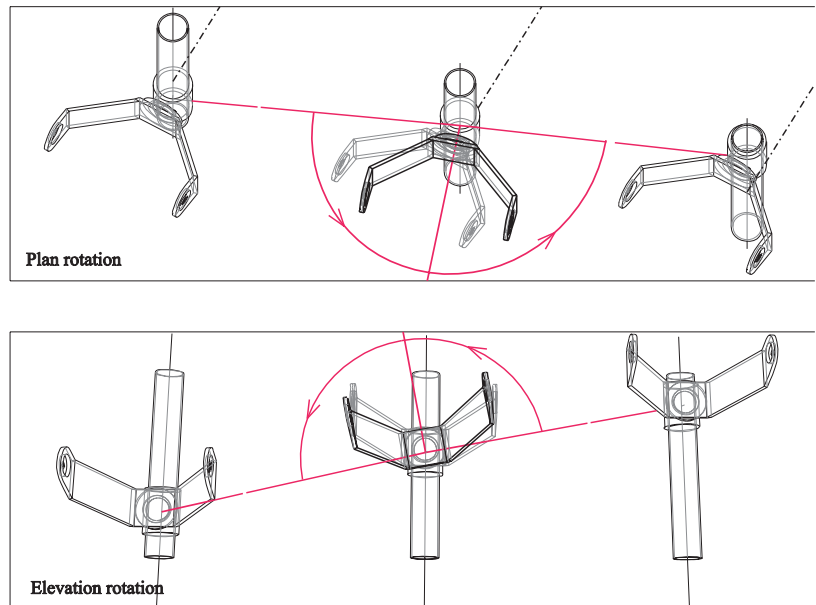◀ Figure 7: Proposed facade, elevation and detail.
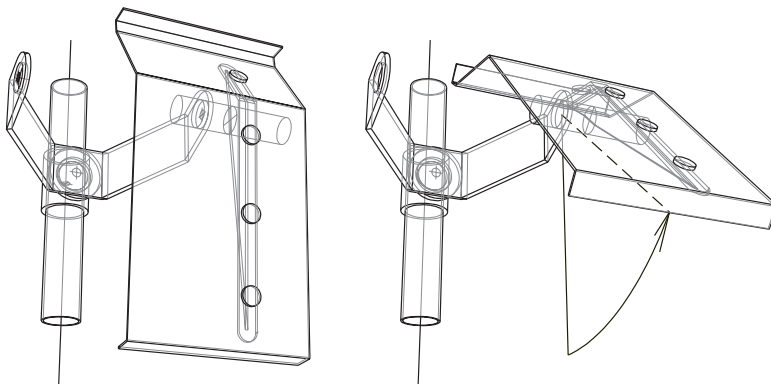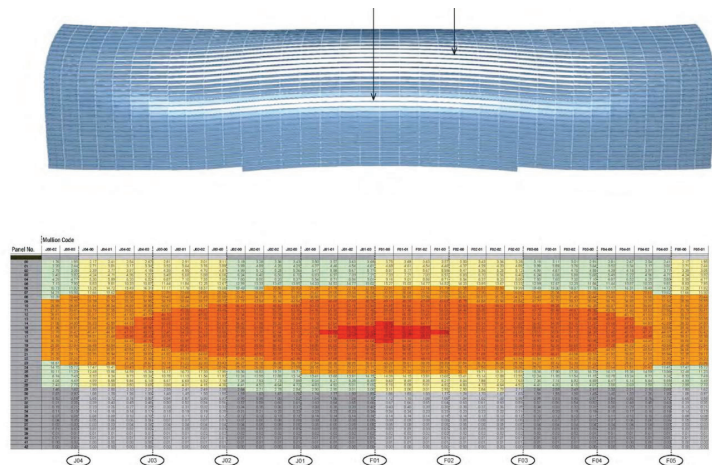

◀ Figure 8: Panel rotation axis.

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► Figure 9: bracket rotation detail.

► Figure 10: Bracket rotation principle.

Plan rotation

Elevation rotation

► Figure 11: Control of panel rotation.
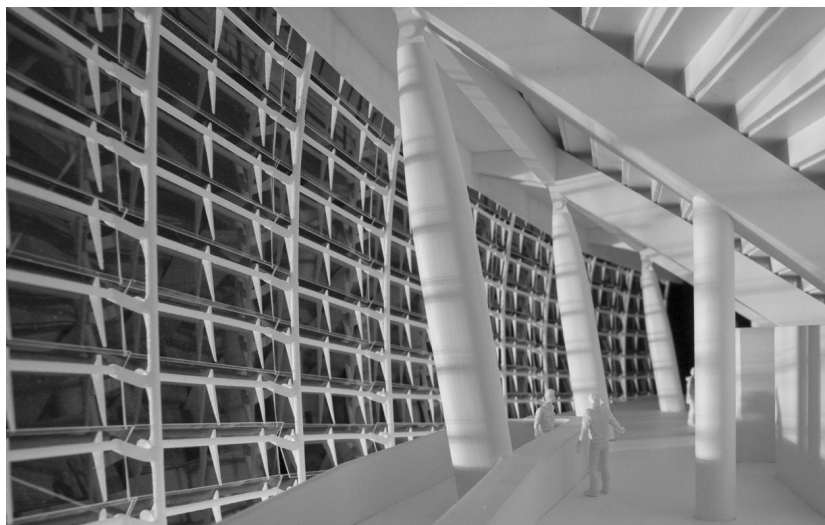
4.1. Construction documentation

The parametric modelling of the facade cladding system required the calculation of all the parameters for configuring rotation angles of panels and brackets and spacing along mullions. Initially this information was not represented in any way other than in the model geometry. In order to document the facade, this numeric information was extracted from the model and recorded in spreadsheets. Together with geometric models, this information was required as part of the construction documentation package (Figure 13). This was issued in a form that allowed a subcontractor to recreate the facade geometry. The data format was developed by closely collaborating with facade subcontractors.

The geometric principles of the facade system were discussed and the content and format of issued information agreed. Based on this, the architectural parametric model was extended to incorporate these requirements. In addition to the numeric information calculated to construct the parametric model, the subcontractors required all panel lengths and two further angles for checking construction tolerances. The facade was divided into sections which were determined by the construction sequence and the radial grid bays. The contractual purpose of issuing construction documentation was to express the architectural design intent and provide enough information to completely reconstruct the system. The subcontractors would then take full responsibility for the detail design and co-ordination of the facade with the knowledge that they had modelled it completely independently. However, in this case the subcontractors chose to use the parametric architectural geometry issued by Populous as the basis for their detailed model of the facade system, thus eliminating any possible discrepancies between desired and as-built geometry.

Inter-bracket distance   bracket angle 01   bracket angle 02

checking angle01   checking angle 02

5. DEVELOPING A COORDINATED CONSTRUCTION MODEL

Detailed fabrication models were produced by the cladding subcontractor using the facade geometry construction documentation described above. Using Dassault Systems' Solid Works, scripts were created to position each element of the facade into a construction model. Key details were developed collaboratively by the architects and the subcontractor. Primary setting out geometry had been established by the architects, this provided the means to co-ordinate between the cladding subcontractor, main contractor and other subcontractors. Detail design decisions could be made by combining the architect's model and with connection geometry proposed by the subcontractors in order to obtain architectural design approval. The reuse of the same geometric model to coordinated subcontractor's work emphasized the importance of the format used by all involved. Populous and the main contractor defined this format and maintained control of the model by establishing key setout geometry and the criteria which all parties adhered to. The difficulty of storing all three-dimensional information from all sub consultants in a single model was amplified by the range of three-dimensional platforms used. However the lightweight setting out system used here was a wireframe model combined with simple written criteria. This model enabled all parties to develop full construction models within their own platform to the level of detail they require for production.

6. MANUFACTURE

Having constructed a fully detailed fabrication model, the cladding subcontractor undertook a process of extracting data sheets and drawings for production and assembly. The cladding system was designed in such a way that the parts could all be manufactured and assembled on the factory

floor or erected into place and connected at height on site in sequence (Figure 14). The mullions were subdivided into extrudable lengths and ordered. The brackets and restraint connections were all cast in foundries, powder coated and shipped to Dublin. The linear sheets of polycarbonate panels were ordered pre-cut to varying lengths, folded and delivered to Dublin. In the subcontractor's factory each assemblage of facade panel was preassembled and packed in reverse order for unloading and hoisting into position on site. Each mullion was laid onto a rigging table and drilled in position to accept the brackets and restraint connections for each part. This part of the process used drawings extracted directly from the fabrication model to define the position and rotation of each drill point. Figure 15 shows a typical mullion drill drawing and the drill rig being moved along the mullion body can be seen in figure 16. Numbering, panel sequencing and bar-coding was all extracted from the fabrication model and used to label all parts assembled in and leaving the factory floor. In parallel, the steel subcontractor underwent a similar process of offsite fabrication of parts and shipping of elements to site. The steel was all manufactured in Italy, packed and delivered by freight to Dublin.
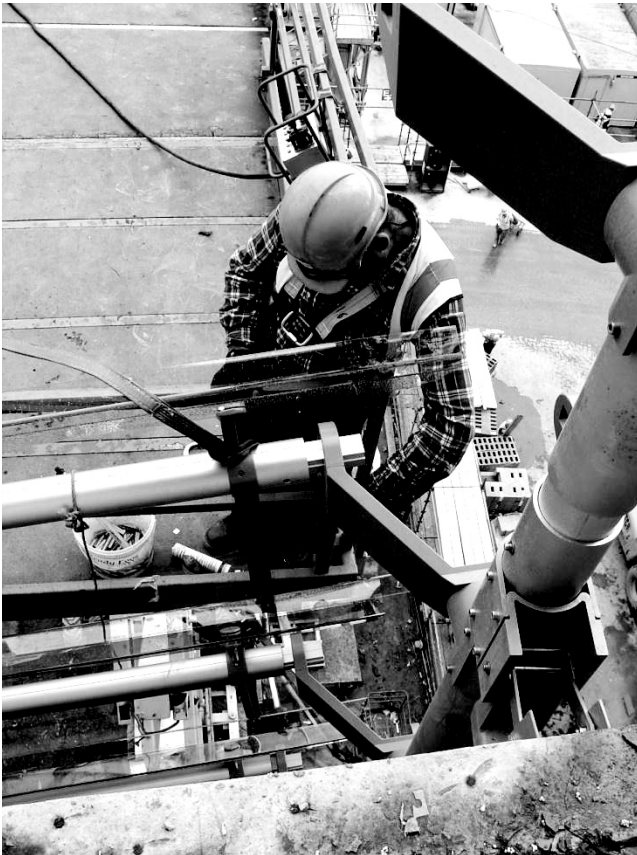
◄ Figure 14: Assembly on site.

► Figure 15: Typical mullion drill
drawing.
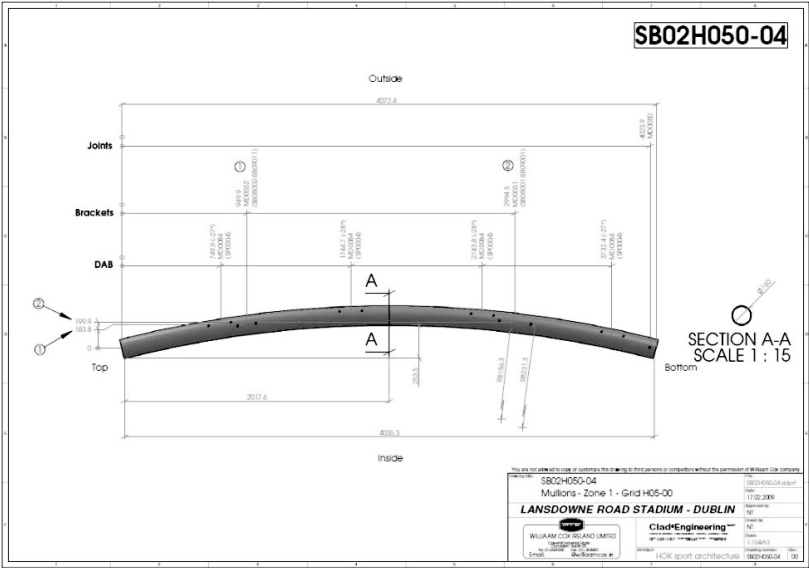
► Figure 16: Drill rig being moved
along the mullion body.

7. CONSTRUCTION

Much of the assembly work was completed off site and the construction operation for both the roof and facade was a sequence of connect and erect. The main steel work was assembled inside the stadium and erected into position (Figure 17). Bolted connection details allowed major parts to be assembled, lifted and connected in position. This was done in sequence using a series of temporary towers to aid the support of the roof's main truss until the structure was completed (Figure 18). The cladding assembly closely followed the steel erection. Once the edge truss frame was in position the cladding mullions with all brackets attached were hung top down in sequence from the roof structure (Figure 19). A cladding panel was lifted onto each mullion and fixed into position. Each panel had a predefined rotation and a pre-drilled and positioned support arm. This meant there was no need for measuring onsite to position parts. In this way any errors could be identified and corrected in the factory and the primary site concern was control of the erection sequence.

◄ Figure 17: Erection of steel work.

► Figure 18: Propped structure.

► Figure 19: Installing facade mullions.

8. CONCLUSIONS

This paper documents the design and construction of the Aviva Stadium Dublin, which used an integrated parametric model across the design disciplines. This novel and innovative approach had many advantages.

The structural engineering team benefitted from having a parametric model built on top of that created by the architects. It allowed them to respond immediately to changes in the overall shape of the stadium without having to spend time rebuilding structural and analytical models to reflect the new geometry, as is typically the case. This meant that the architects could quickly get feedback on the structural implications of their design decisions and a more optimal overall design was possible.

The extra time required to create the link between parametric model and analysis was also a good investment. Without it, the analysis would lag behind the design, since the loading used for analysis would have to be conservatively based on approximate bay-widths and member sizes. By having a parametric analysis model, a much more accurate representation of the loads was used at all times with no extra effort, leading to a better understanding of the structural behaviour and a more efficient design.

The process undertaken by the architects was to use a single parametric model as both a design tool and a coordination platform. This model was also a key asset in the manufacture and construction process. It allowed a clear sequence of events from the design of the project in conceptual stages through to completion. This clear process enabled management of the intricacies of coordinating building trades associated with such a complex construction. The process placed the architect firmly in control of the project and allowed a complex building framework to be precisely established.

The concept of using a single parametric model across a multi-disciplinary team, and sharing data intelligently with engineering analysis software and manufacturing processes has led to an efficient and inspiring design. This success has been recognized through the long list of construction industry awards bestowed on the project team, including the Irish Concrete Society's Overall Award and Best Building Award 2011, RIAI's Best Leisure Building 2011 and RIBA's Architectural Excellence (EU) 2011.

Since the completion of the Aviva Stadium design, other CAD software vendors have begun to include parametric modelling capabilities in their standard off-the-shelf products, the use of which is fast becoming the norm. However, it is not until these models are shared amongst all members of the design team as a matter of course, and engineering analysis applications are fully integrated, that the true benefits of a parametric approach to building design can be realised.

Acknowledgements

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