The Smithsonian Courtyard Enclosure

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A CASE-STUDY OF DIGITAL DESIGN PROCESSES

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This paper outlines the processes involved in the design of the Smithsonian Institution's Patent Office Building's new courtyard enclosure. In 2004, Foster + Partners won an invited international competition to design the new courtyard enclosure in Washington, D.C. Early in the project, the Specialist Modelling Group (SMG), an internal research and design consultancy, was brought in to advise the project team on computer modelling techniques, develop new digital design tools, and help solve the complex geometric issues involved. Throughout the project, computer programming was used as one of the primary tools to explore design options. The design constraints were encoded within a system of associated geometries. This set-out geometry performed as a mechanism to control the parameters of a generative script. The design evolution involved the use of many different media and techniques and there was an intense dialog between a large team and many consultants. The computer script was a synthesis of the design ideas and was constantly modified and adapted during the design process. The close collaboration between architects, consultants, and fabricators was of key importance to the success of the project. This project, now named The Robert and Arlene Kogod Courtyard, will complete in late 2007.

FIGURE 1 Norman Foster's Concept Sketch for the Canopy

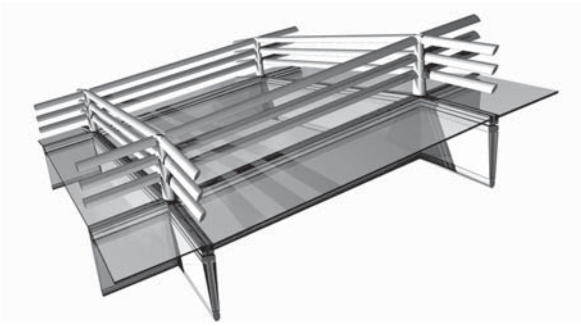

FIGURE 2 Beam Detail of the Competition Scheme Canopy

THE PATENT OFFICE BUILDING

The Patent Office Building in Washington, DC, was built between 1836 and 1867. The original designs for the building were by the architect Robert Mills. The porticos were modelled after the Parthenon in Athens, and it is considered one of the finest examples of Greek Revival Architecture in the United States. The south wing of the building was completed in 1840. The east, west, and north wings of the building were completed at later dates under the supervision of different architects. The four wings of the building are constructed around a 2500 square metre open-air courtyard. This central courtyard's south elevation and portico are constructed of sandstone, while the elevations of the remaining wings are granite.

One of the oldest federal buildings in Washington, the Patent Office Building was originally built to house the many scale models that patent law required inventors to submit. Once described by the poet Walt Whitman as "the noblest of Washington Buildings," it housed the Patent Office from 1842 until 1932. Congress gave it to the Smithsonian Institution in 1958. The Patent Office Building now houses the Smithsonian American Art Museum and National Portrait Gallery (Smithsonian 2003).

THE ARCHITECTURE COMPETITION

In 2000, the Smithsonian began a six-year renovation project to restore the building. The project involved extensive renovations including a new roof, mechanical systems, electrical and lighting systems, a new auditorium, and a new conservation centre. In the fall of 2003 the Smithsonian held an invited international architecture competition for an enclosure to the central courtyard. The competition called for a visionary proposal, an urban centrepiece for Washington, a public room within the city, and a commitment to design and innovation (Smithsonian 2003).

FIGURE 3 Competition Model

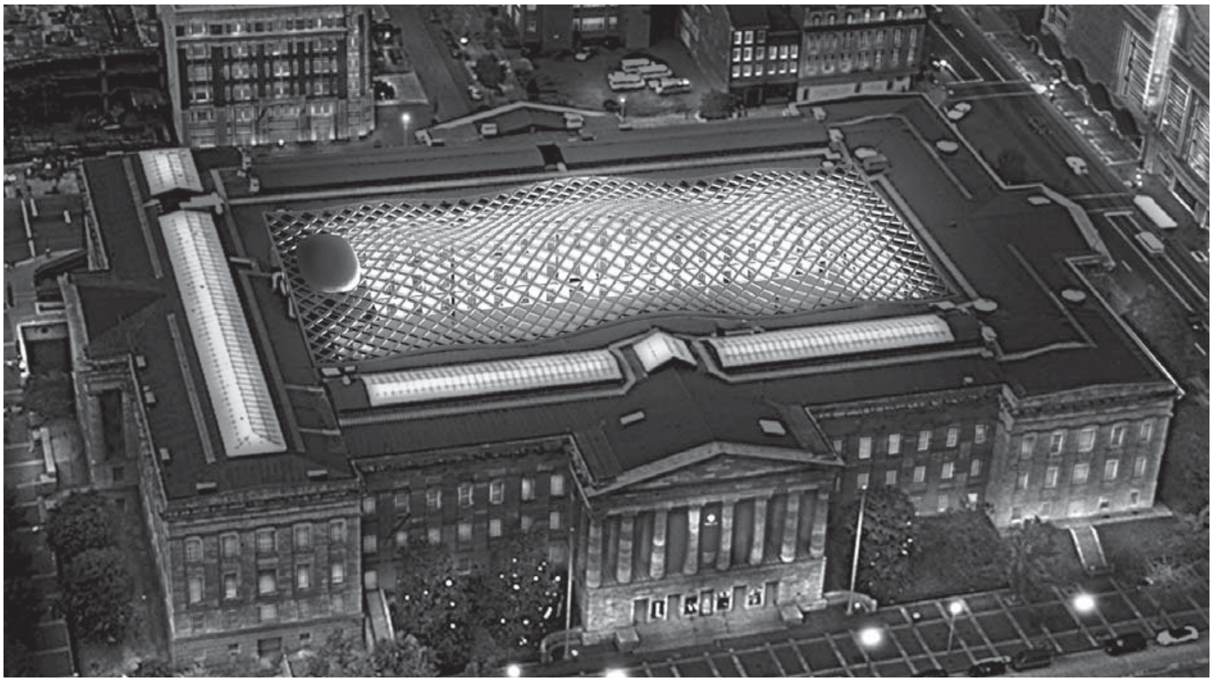

FIGURE 4 Courtyard Canopy seen illuminated at night

The Foster + Partners scheme encloses the building's grand central courtyard with a flowing glass canopy. The scheme aims to transform the public's experience of the building, and creates a flexible events space capable of holding receptions, performances, seated dinners, and landscaping. Designed "to do the most with the least," the fully glazed canopy develops structural and environmental themes first explored in the design of the Great Court at the British Museum (Foster + Partners 2005).

The courtyard canopy is supported above the existing parapet on eight columns. The integrated design solution was a gently undulating lattice shell that efficiently dealt with the structural requirements, provided protection from the rain and snow, acted as a giant acoustic absorber, and provided a sun shading and natural lighting solution. Norman Foster's concept sketch (Figure 1) shows the diagonal grid of structural elements gently flowing over the central courtyard.

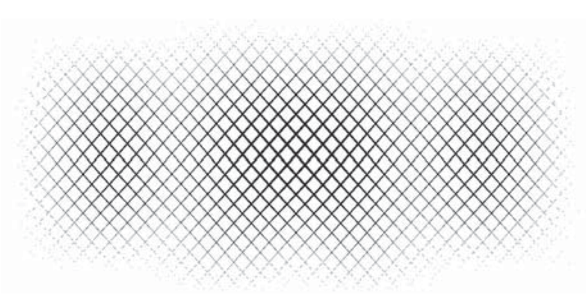

FIGURE 5 Plan of Twisting Beams

THE SPECIALIST MODELLING GROUP

The Specialist Modelling Group (SMG) acts as an internal consultancy within Foster + Partners. Its group members have expertise in complex geometry, environmental simulation, parametric design, computer programming, and rapid prototyping. The SMG brief is to carry out project-driven research in the intense design environment of the Foster + Partners office. The group consults in the areas of project workflow, digital techniques, and the creation of custom CAD tools. Its specialists work with project teams on either a short or long-term basis and are involved with projects from concept design through to fabrication (Peters and De Kestelier 2006).

The proposed canopy was composed of a diagonal grid (dia-grid) of structural fins. Similar to the structural solution at the Great Court the fins form a warped,

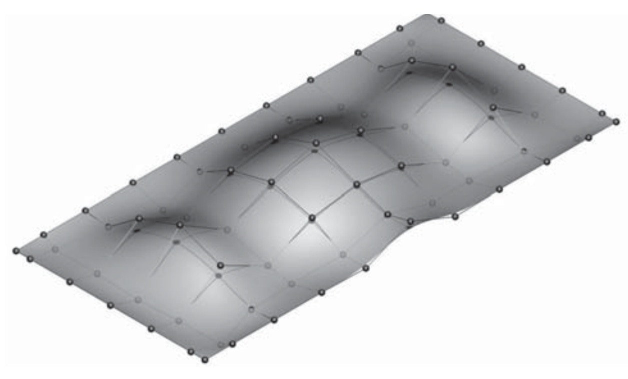

FIGURE 6 Canopy Design Surface with Control Polygon

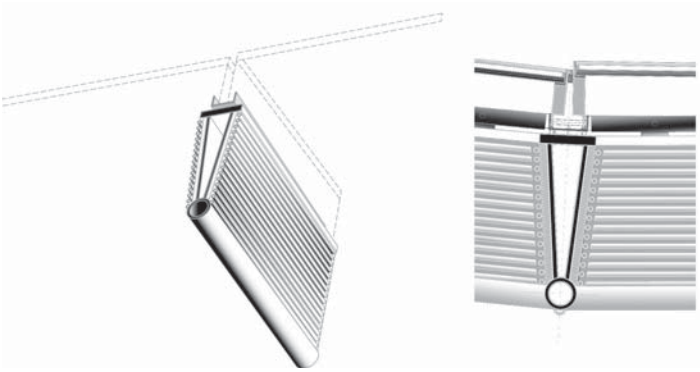

FIGURE 7 Beam Detail–Isometric Section and Section

lattice shell structure; however, unlike the structure at the Great Court the fins here perform many other functions beyond simply the structural. For the competition proposal, the glazing was attached at the mid-point of the depth of each fin. Above the glass the fins are louvers providing solar control, beneath the glass the fins become structural elements. These structural fins are perforated, allowing sound to be absorbed by the acoustic absorbing material beneath. The grid of diagonal fins provide an elegant structural solution, protection from the harsh climate, environmental control of light, and an acoustic environment suitable for theatre, music, or social gatherings. A detail of the canopy structural and glazing components is illustrated in Figure 2.

The SMG was invited to join the design team early in the competition stage to create a parametric model of the canopy and its twisting fins. The SMG has developed many custom digital tools through its participation in various design projects. These digital tools are often in the form specialized computer programs. The generalised versions of these digital tools will later be added to a special SMG tool bar on the Foster + Partners MicroStation menu.

For the Smithsonian project, the SMG created a computer program to draw the twisting structural fins, and another computer program was written to create the glazing panels. The panels were analysed for panel twist, area, and slope. The SMG analysed different canopy options to determine the effectiveness of different louver and structural configurations; these analyses were done using the software package Ecotect. The SMG Flatpattern tool was used to flatten the twisted beams into 2-D shapes so that they could be cut out using a laser-cutter. The cut and notched beams were easily assembled. Figure 3 shows the competition model with the canopy made from the laser-cut beam strips.

CAPTURING DESIGN INTENT

Instead of the simple translation of the designer's sketch, capturing design intent involves the creation of a digital schematic that can be easily used by designers to manipulate complex geometry. It is crucial to understand the design's driving factors and know where the physical limits and technical constraints of the design lie. Capturing design intent involves the careful definition of parameters and an understanding of how these parameters will change the digital model as they are modified.

The overall form of the canopy is one that is rectangular in plan, just larger than the courtyard below, and maintains a constant height around its edge. The canopy form undulates along its long section, dividing the structure into three domed bays. Eight perimeter columns support the canopy. The undulating form is highest in the middle bay, where the span is also the greatest at about 36 metres. The new canopy design respects the existing building by over-sailing at both the parapet and portico conditions. The junction between old and new is hidden by this overlap. It was important that the canopy remain invisible from the nearby streets, maintaining the integrity of the historic facades; however, from farther away on Pennsylvania Avenue, this canopy will be seen to float above the Patent Office Building. Figure 4 is an image from the competition submission showing the illumination of the courtyard at night.

Structurally, the canopy is composed of three interconnected vaults that flow into one another through softly curved valleys. When viewed over the long section, the four saddle points derive from the column locations. These four low points form a run-off for rainwater that will be discharged through the drainpipes located in the columns. All water run-off from the new enclosure occurs through the new columns; no water is discharged onto the existing structure. Unlike the British Museum, where the new courtyard enclosure is seen to rest on the existing structure, the existing structure of the Patent Office Building could not take any additional load; so, the entire canopy structure is supported by the columns. The columns provide for vertical as well as lateral loading; they had to be strong enough to withstand snow and wind loads as well as earthquakes and bomb blasts.

The sinuous form of the canopy is coupled with a diagonal grid of twisting beams, which form a rigid lattice shell supported by the columns. The beams also provide important environmental and acoustic control for the interior space. The sides of the beams carry the acoustic absorbing material; as such the depth of the beams was driven not only by structural parameters, but equally by acoustic parameters. The design strategy during the competition phase was to orient the beams vertically at the perimeter of the canopy, at column locations, and between columns. This both increased structural performance in these areas and allowed light into the galleries, see Figure 5. In the centres of the domes, the beams were twisted to prevent direct sunlight from the south and allow in even, indirect light from the north.

CONTROL SURFACES

The design constraints and decisions were encoded in a system of control geometries: a design surface, a law surface to control the twist in the beams, a set out grid surface, and centreline markers indicating column locations. These geometries were used as inputs into a computer program. This program generated all of the structural and glazing components. One of the critical ways in which a tool can prove to be useful or useless is through its control mechanism; it is important that the control mechanism be simple and intuitive. In order to make the control surfaces simple to manipulate, these surfaces were made to have the simplest possible control polygon—the “minimal control polygon.” With fewer points to control, not only was it easy to make the fine adjustments that were necessary, but also it made it difficult to create a surface with sharp, discontinuous, or uneven curvature. The design surface with its control polygon is seen in Figure 6.

The design surface controlled the form of the canopy. It was the surface onto which the glazing and structural components were populated. The canopy’s geometry changed throughout the project as the form adapted itself to changing design constraints. The domes were adjusted to meet sightline restrictions, and the depth of the valleys between the domes adjusted to tune structural performance. The height of the design surface at the column locations was adjusted to achieve proper drainage, and the geometry responded to each unique edge condition. The control surfaces allowed the simple manipulation of the complex geometry of the canopy as the design developed.

During the competition phase, the smooth, gradual twisting of the beams was achieved by using a law surface to control the twist. The law surface had the same plan extents as the design surface, and acted as a three-dimensional law curve. The amount of twist at any node point was found by taking its X and Y values and then measuring the z-height of the law surface at this location. This value was multiplied by a constant to get the amount of twist at that node. The grid surface, also matching the design surface in the X and Y plan dimensions, controlled the spacing of the node positions in plan. In combination with these surfaces, the column locations were mapped using centreline markers.

The twisting beam strategy was altered during the design process. Environmental performance was achieved through the use of high-performance glass coatings so it was no longer necessary for the twisting beams to provide shading for the courtyard. The structurally efficiency of the beams was improved when they were oriented normal to the design surface. The louvers above the glass surface, as proposed in the competition-winning scheme, were not used as they increased the apparent beam depth when viewed from inside the courtyard and they would have interfered with the maintenance of the glazing. A diagram of the beam detail as constructed is shown in Figure 7.

SKETCHING BY ALGORITHM / GENERATIVE LOGIC

An algorithm is a finite list of well-defined instructions for accomplishing a task. According to Chris Williams, each rule of an algorithm can only be interpreted in one way—it requires no intelligence to understand. However, when people design they will adopt a set of rules, but these rules will be vague, incomplete, and contradictory—they require intelligence to decipher (Williams 2004). The writing of a computer program that generates architecture requires the ability to understand and

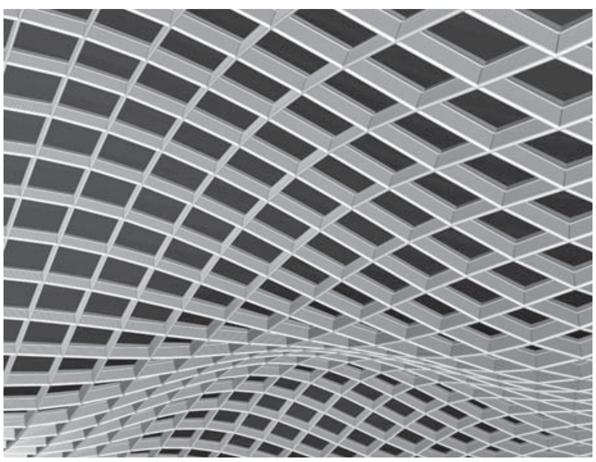

FIGURE 8 Underside of the Canopy

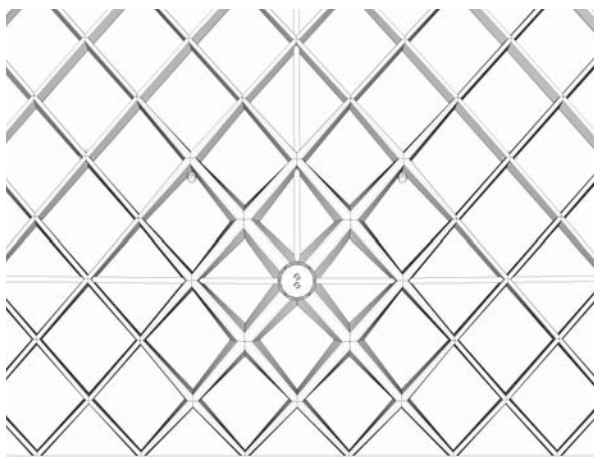

FIGURE 9 Beam structure at column location

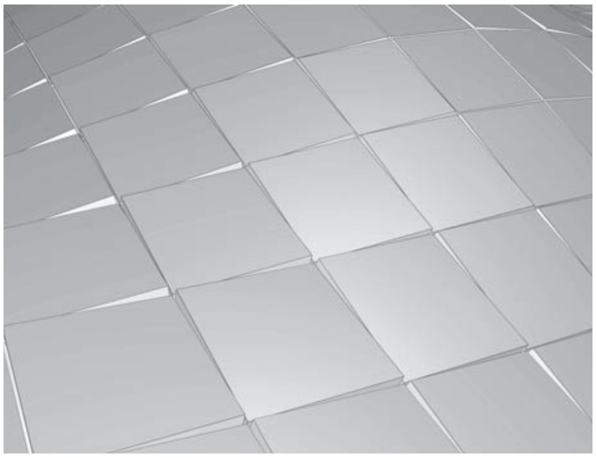

FIGURE 10 Courtyard Enclosure Flat Glazing Panel Strategy

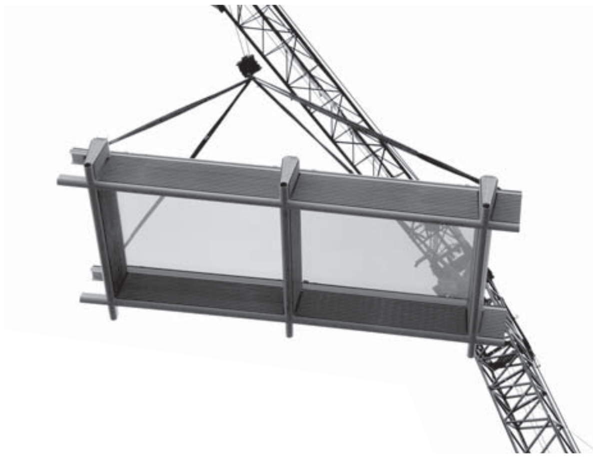

FIGURE 11 1:1 Mock-up of Beam and Glazing Components at Gartner Factory

interpret of the design intent and then translate this into algorithms that the computer can understand.

The algorithms used in this project were not predetermined, but developed incrementally during the project. The creation of custom computer programs was a technique that was used from the very beginning of the project. As the design became more specific in its requirements, the original beam generation program was altered and added to. This program developed as the design progressed and became a synthesis of the design ideas. This complex generative program consisted of many sub-modules. The program was controlled by a series of parameter values and by the geometry of the control surfaces. The parameters were often numeric values, but could be option switches. MicroStation Visual Basic for Applications (VBA) was used as the programming language for the source code that generated the geometry of the canopy.

Many investigations were still done using traditional three-dimensional CAD tools, but once the design logic was determined, these rules were added as algorithms to the generating computer program. The rules that generated the canopy geometry are simple; however, the end result has a high degree of complexity. While the geometry at each node differs, the rules that drive that geometry are the same for each node. While the internal logic driving the geometry of each beam is the same, the physical form of each beam is unique. The canopy structure and glazing panels adapt in response to the local geometry of the design surface and to the proximity of column positions. At each node the structure is normal to the design surface, and so beams twist from node to node. When seen from below, the beams seem to gradually and elegantly twist as they diagonally traverse from one side of the canopy to the other, as shown in Figure 8. The structure thickens gradually, both in depth and width, as it gets near to the columns, as shown in Figure 9. This is to accommodate the increasing structural forces at the column positions.

Computer programming allowed for the independent development of canopy geometry and individual component strategies. The set out geometry of the control surfaces could be altered without affecting the logic of the beam section or cladding system; and, likewise, within the generating code, different modules of source code could be inserted, removed, or edited to create new canopy options. Using this approach, the long-chain dependencies of a fully associative CAD software system did not exist, design modification was simpler and regeneration much faster. When changes were made to the generating program or to the set-out geometry, a new digital model could be generated rapidly. A dynamically parametric model was not necessary.

The final version of the generating code was over 5000 lines in length and had 57 parameters. Using only the set-out geometry as input, the script generated approximately 120,000 elements in about 15 seconds. Over 400 models were generated over six months.

PANELISATION STRATEGIES

Though much of its work involves complex geometry, the role of the SMG is often not the proposition of those forms, but the search for their means of description. This rationalisation of complex surfaces has led to using surfaces that produce planar quadrilateral panelisation, such as surfaces of rotation, in particular toroidal forms, and surfaces such as sheared cones and translational surfaces (Whitehead 2003).

The design surface of the canopy ideally would have also been the glazing surface. However, the design surface had double curvature and the glazing nodes were already well defined by the location of the structural

FIGURE 12 Test Assembly of Beam Components at Gartner Factory

nodes which, in turn, were already well defined by the planning grid. A panelisation solution that would produce planar quadrilateral panels was not obvious in this case. Two options that were studied were the scale-translational surface and the triangulation of each of the quadrilateral glazing panels. With the scale-translational surface it was difficult to achieve the correct surface geometry—the glazing node points no longer matched the structural node points. The triangulation of the glazing panels was a workable solution, but it was ultimately not considered because the quadrilateral panels allowed more sky and less structure to be visible from inside the courtyard, and in this case, it was found that the quadrilateral panels simply looked better.

In order to achieve a planar quadrilateral solution on the doubly-curved design surface the glazing node points had to be moved away from the ideal location. Different options of how to achieve this were studied. As three points define a plane, only one of the quadrilateral panel's node points needed to be displaced off of the design surface. However, this produced some rather extreme displacements, in particular at locations that had a high degree of curvature. The solution that was used maintained two of the four glazing nodes on the design surface, while the other two were displaced above the design surface to equal amounts, in this way halving the otherwise more extreme displacement. The planar, glazing panel solution is shown in Figure 10.

FORM EVALUATION AND SHARING INFORMATION WITH CONSULTANTS

It is possible to generate hundreds of thousands of different options by using computer programming as a generative technique—many more than can be individually studied and considered. It is important to understand the design constraints to establish the range of possible options. It is then important to have a clear strategy for evaluating the many generated options that lie within the solution space. There were many methods by which the design was evaluated: structural, environmental, acoustic, and aesthetic. While there was no attempt to automate the feedback process, it did prove beneficial to work closely with consultants to better understand their data input needs for their analyses. By building the production of this information into the generating computer program, the generation and analysis cycle could be shortened, and the design could reach an optimal condition balancing the diverse design strategies.

Each digital model produced by the generating computer program contained multiple representations of the design: a centreline model for structural analysis, a triangulated flat panel model for acoustic analysis, a simplified model for hidden line visualisations, a lighting node position model, node and beam set-out drawings and spreadsheets, unfolded beams for the digital fabrication of scale models, and a complete digital model of all canopy elements for the creation of drawings by the

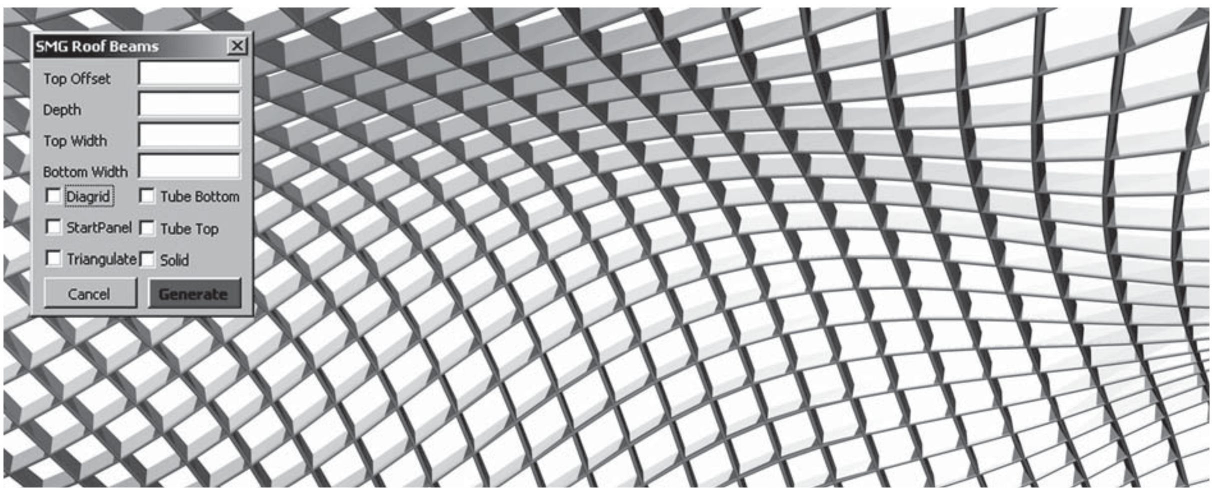

FIGURE 13 SMG Roof Beams Computer Program

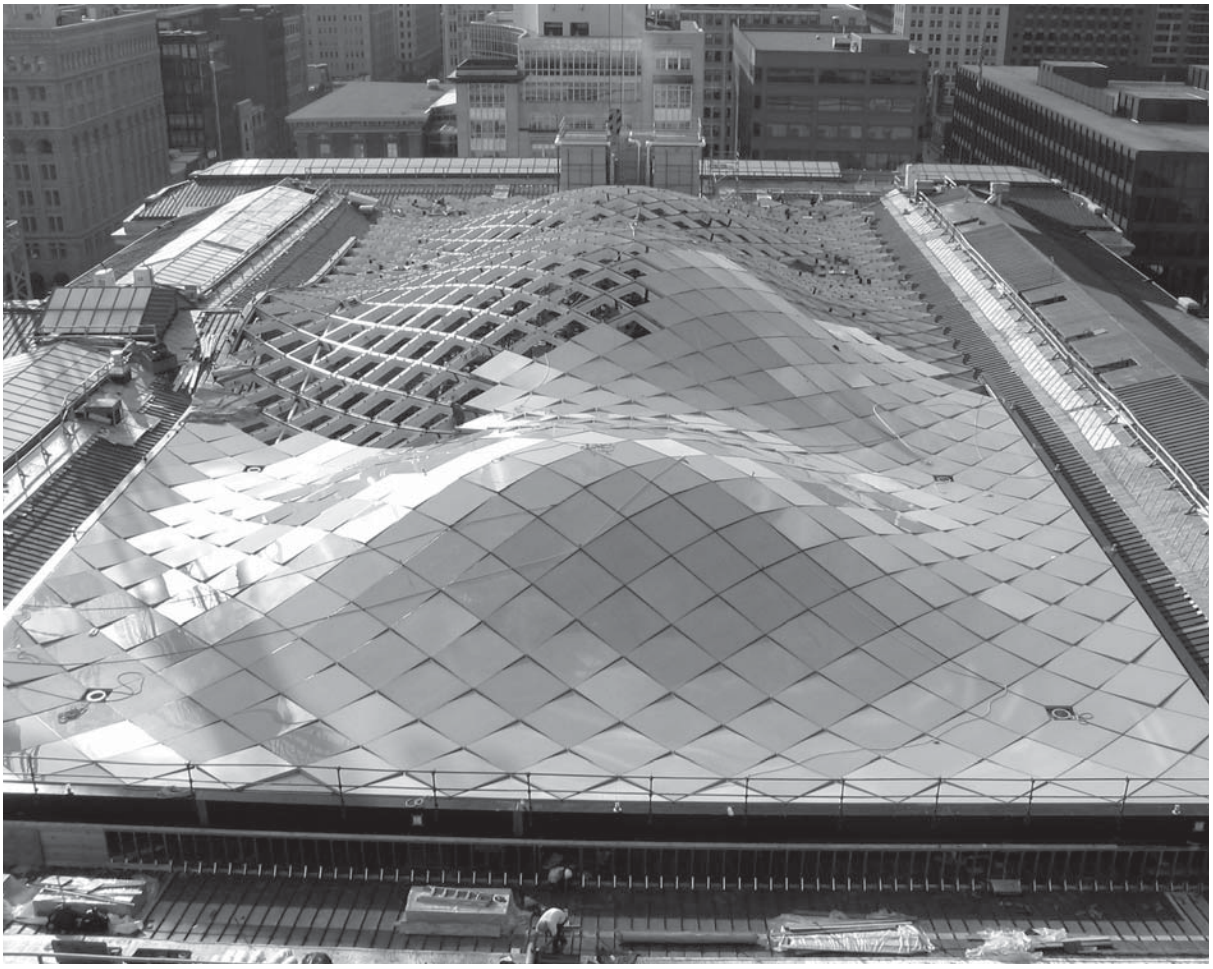

FIGURE 14 Canopy under construction

project team. The computer-generated model gave very precise control over the values and relationships within the roof system. It produced consistent and repeatable results. The design history could be saved as a copy of the generating script and the set-out geometry used. The centreline model and node data sheets were shared with structural engineers, Buro Happold; the simple, triangulated model was shared with acoustic consultants, Sandy Brown. However, the 3-D model was not shared directly with the fabricators.

Rather than share the digital model directly, fabricators are required to develop their own digital model of the project. This is done to ensure that the fabricators have fully understood the geometry of the canopy, and will therefore be less likely to have misunderstandings or make mistakes. The method by which the geometry was explained to them is through the Geometry Method Statement (GMS). This is a tool used by Foster + Partners to describe the project in terms of its geometric set out and node positions and connectivity. The geometry method statement is a simple set of rules and relationships that, if followed correctly, result in the determination of all the necessary set-out information for the project. The geometry method statement is broken down into easy-to-follow, basic geometric operations that can be carried out on any CAD system, or even using a ruler and compass (and maybe a calculator).

FABRICATING COMPONENTS

Most previous projects at Foster + Partners have involved the rationalisation of free-form geometry into arc-based constructions (Whitehead 2003). This was not the case for the Smithsonian courtyard enclosure. In this case, the use of free-form (B-Spline) surfaces was necessary to achieve the desired form, and the use of computer programming as a generative tool allowed for the generation of complex components. The only way in which a design of this complexity could be realized was through a close collaboration between designer and industry, and to involve the fabricator as early on in the design process as possible.

The fabricator of the canopy was Joseph Gartner GmbH, located in Gundelfingen, Germany. Gartner is a manufacturer of custom-made aluminium and steel facades. A cladding tender package was put out in the summer of 2004, and from this Gartner was chosen from the competing companies as a preferred fabricator for the canopy structure and glazing. Foster + Partners together with Buro Happold as structural engineers provided the architectural and structural design intent, but by working closely Gartner the design developed so that it could be more easily realized. It was critical to work closely with industry in this way to ensure that the project was the best product all parties could produce.

In order to produce their digital model Gartner employed Arnold Walz Architect, an experienced specialist in creating the digital parametric models and complex geometries. Working through the Foster + Partners Geometry Method Statement (GMS), Walz created a design surface using the Rhinoceros NURBS modelling package. He then used this design surface as one of the inputs into a computer program written in AutoLISP running in Mechanical Desktop. Using the geometric rules set out by the GMS his computer program generated a wireframe model of the canopy and a huge database of point and connection information. This wireframe model contained all necessary beam elements, glazing panels, thickenings and intersections of the approximately 10,000 pieces that would need to be cut and assembled to build the canopy. Once this wireframe model and database was generated a solid model of each beam could be generated individually. "From the viewpoint of scripting (the geometry) is simple … each point is complicated, but once you have one, you have them all"(Walz 2007). Similar to the Foster + Partners approach, a dynamic parametric model was not created, nor seen to be necessary.

The building of 1:1 mock-ups was of critical importance to the decision making process. Gartner, at several points during the design process, built 1:1 mock-ups of sections of the canopy for inspection by the design team. These test pieces were lifted to a height of 17 metres to understand what the components would look like when viewed from the courtyard floor. One of these mock-ups is shown in Figure 11.

The structure for the canopy components came from four steel contractors: columns, column capitals, standard beams sections, and thickening beams sections came from four different sub-contractors. The columns were constructed from 50 mm thick rolled steel. The column capitals were produced using sand-casting process. They were cast in about 30 seconds from about 8 tons of steel. This was then reduced to about 4 tons through later cutting, sanding and milling. The beams were cut from flat sheets of steel with plasma cutters using 2-D CAD files as input. Gartner was allowed to re-engineer and re-design the structure in order to rationalise and economise the design. Since all pieces of the canopy are unique, components were carefully marked with identification numbers or with barcodes making components traceable and locatable within the design. The beams were then assembled upside down on carefully constructed custom jigs into ladders in the Gartner factory in Germany to assure that tight tolerances were achieved, as shown in Figure 12. The ladder size was determined by both shipping constraints (the size of shipping containers) and by the site crane's lifting capacity (8 tons).

CONCLUSION

The Patent Office Building is one of Washington, D.C.'s most historic buildings. It currently houses the Smithsonian Institution's National Portrait Gallery and Smithsonian American Art Museum. It is currently undergoing an extensive renovation. The international architecture competition for the design of a new courtyard enclosure was won by Foster + Partners in 2004.

All of the geometry for the new Smithsonian Courtyard Enclosure was generated using a single, custom written computer program. Programming was used as an important tool throughout the design process, not just as a tool to generate a final model. This computer program was developed with input from all the design consultants. The intent of this generating script was to develop the design: to develop a tool with the ability to explore a large range of design solutions, to provide the data necessary to evaluate these options, and to be flexible and adaptable enough to cope with the large lateral shifts that sometimes occur during the design process. The data produced by this computer program was used by the designers to generate drawings, by the SMG to carry out environmental and geometric analysis, and by consultants to carry out their specialist analysis. Though the development of this computer program required specialist knowledge, its operation did not. The design team could generate new options of the design using the generating code and the simple and easy-to-manipulate control geometry. Segments of this computer program were later re-used to create new generic digital tools such as SMG Roof Beams, shown in Figure 13.

The close collaboration between design team and fabricator was of key importance to the success of the project. Joseph Gartner GmbH, the fabricator, brought to the project their expertise in methods of fabrication of glazing and structural components. Through their involvement in the project from the early stages of design, the designers could be assured that what they were proposing could be built. While ultimately the digital model was not shared with Gartner, the drawings and methods were. The geometric algorithms that were written into the computer program were synthesised into a series of simple operations and issued as a drawing set, the Geometry Method Statement. Gartner, having understood the generating principles, then created their own digital model and fabricated and constructed the canopy. See Figure 14.

This project, now named The Robert and Arlene Kogod Courtyard, will be completed in late 2007.

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