Atrium Roof Structural Artistry

The Olin Business School at Washington University in St. Louis

By John P. Miller, P.E., S.E. and Marc A. Friedman, P.E., S.E., LEED AP

Figure 1. Interior view of completed atrium. Courtesy of Alan Karchmer.

Most structural engineers are creative in the sense of finding a structural solution to an architectural challenge, but they are not often thought of as artistic. Once in a great while, a design team and an owner come together and the whole is truly more than the sum of its parts. This was the case with the new Knight Hall and Bauer Hall, the new building for the Olin Business School on the Danforth Campus of Washington University in St. Louis. Structural engineer KPFF Consulting Engineers took an active artistic role with the architect in developing a unique roof structure. While there are many interesting structural aspects about this beautiful new $70 Million, 177,000 square foot building to accommodate faculty, numerous large classrooms, a 300-seat auditorium, and a magnificent multi-functional atrium space, the atrium roof structure deserves special emphasis as a work of structural art.

The building footprint is generally U-shaped and organized around a roughly 90- by 90-foot atrium space. Tiered seating is carved from the lower floors of the atrium to create a forum. The architectural firm of Moore Ruble Yudell Architects & Planners of Santa Monica, CA working with Mackey Mitchell Associates and the Owner wanted this space to be light-filled and open, able to host large and small functions, and to serve as an informal gathering space. It was obvious that this place needed to be surrounded by a very special structure, and the atrium roof was to be the architectural centerpiece of the Olin Business School expansion project.

Structural art is defined by three guiding principles known as the 'Three Es': Efficiency, Economy, and Elegance. Structures that minimize the use of materials while they safely carry loads are efficient; ones that are less costly in terms of construction are economical; and structures that are pleasing to the eye are elegant. All three of the Es must be present in a structure to be characterized as structural art. Starting with a blank canvas, the design team seized the opportunity to compose a beautiful glass-covered work of structural art.

Design Constraints

The atrium space was to be column-free, so the atrium roof structure would be supported on its perimeter. It was preferred not to have any roof structural systems with a bottom horizontal plane, since this would tend to reduce the soaring volume of the space. The west wall and part of the south wall would be all glass, and the spring-line of the atrium roof structure would be a few feet above the surrounding U-shaped main building. Therefore, there would be no rigid perimeter means to resist horizontal thrust from the roof structure, and these forces would need to be resolved internally. It was also desired to have some roof surfaces angled to the south or vertical to regulate the sun, add ventilation, or to use for solar arrays. Because this roof structure would be on the interior of the building footprint, at the farthest reach from both of the tower cranes, it would be important to be able to erect the structure in small, manageable sections.

Evolution and Symbology of the Roof Form

Elegant and mysterious. These were the two words Buzz Yudell of Moore Ruble Yudell used to describe what the atrium roof structure should be within the context of the building. The roof form evolved by studying

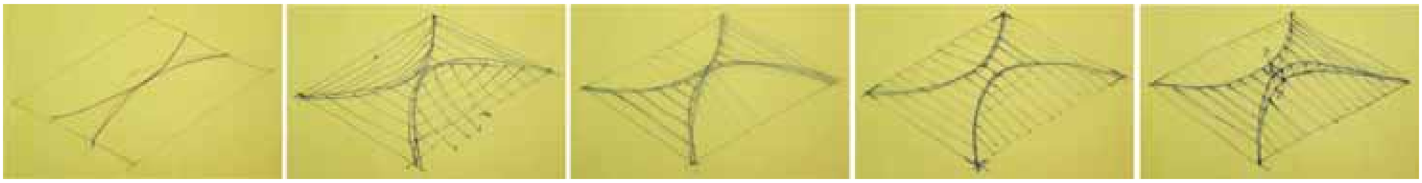

Figure 2. Buff sketches showing conceptual evolution of the atrium roof structure.

numerous structural concepts, generally categorized as "compression type" and "flexural type." Compression type forms rely on stiff perimeter members to resist horizontal thrust and vertical deflections, while the members that span over the space are generally in compression. Several different compression type structural concepts were studied, including wood and steel lamellas, various arched notions, and several configurations of steel domes. All of these roof structures were quite elegant, and they could be made relatively thin and soaring, but they all required uneconomical perimeter framing to resist thrust and deflection. None of them were particularly mysterious, meaning one could look up at it and immediately resolve the forces with the eye.

Flexural type forms rely on bending stiffness of the structure to resist vertical loads. A series of flexural type structural concepts were imagined such as arching trusses, various pin-connected trusses, and undulating flexural members. While these designs minimized the thrust problem and were relatively efficient and economical, they encroached into the volume and were fairly common looking.

A breakthrough came one day with a roll of yellow tracing paper, and sparked a very iterative design process between KPFF and Moore Rubel Yudell. What if two arches leaned on each other? Why not move them to the corners, where the compression could be resolved?

Then the arches were pulled apart, vertical surfaces were created by lowering a roof plane surface on both sides, and the leaning arches became curved trusses. The spaces in between were filled with various forms of flexural secondary members that had very little thrust, which set up an interesting visual hierarchy. Now we had a soaring roof with the spatial focus of a dome, but with a dynamic modern expression. The curved trusses also recall the iconic form of St. Louis's Gateway Arch, just seven miles east, which is a symbol of the westward expansion of the country.

Geometric Basis of the Roof Form

In order to accurately model, analyze, render, and ultimately construct the roof structure, geometric parameters needed to be established that resemble the art form. *Figure 3* illustrates the intersection of two sloping planes and a cylinder, forming two ellipses. These ellipses define the top chords of the elliptical trusses. To form the bottom chords of the elliptical trusses, two more sloping planes intersect vertical surfaces projecting through the top chords (*Figure 4*).

Structural Flow of Forces

Secondary trusses collect load from the glass panels and deliver it to the elliptical trusses and the perimeter ring beam. The elliptical trusses, primarily through axial compression, carry the load to the corners of the structure where the perimeter ring beam resolves the forces in tension. The top HSS chords of rod trusses at the center of the roof also serve as compression struts between the elliptical trusses.

Structural Loading and Analysis

The atrium roof structure was modeled and analyzed using RISA 3D. Load cases and load combinations were defined using ASCE 7-05. Load cases include dead, live, snow, wind, seismic, and temperature. In particular, unbalanced snow and wind loads were given careful consideration. In total, 197 load combinations were analyzed. Basic loads were applied as line loads to the secondary members. Steel rods were modeled as Euler buckling members.

The elliptical trusses consist of a round HSS18 top chord, 6-inch standard pipe verticals, rectangular HSS bottom chords, and steel rod web members. The trusses are separated by ten feet at their apexes. Three pipe X-braces connect the two elliptical trusses at their apexes to resist unbalanced vertical loads.

The secondary infill members between the elliptical trusses are generally of two types: parallel-chord steel trusses and rod trusses, the depths of which vary in proportion to their span length. The steel trusses span one direction and form sloping planar roof surfaces on the north and south sides of the roof, and are comprised of rectangular HSS top chords to receive the glass roof panels, with steel pipe bottom chords and diagonal web members. All truss panel points and top chord bridging elements align with the glazing system they support. The steel trusses are designed to be as small as possible to achieve lightness, and so bottom chord compression under wind uplift is resisted by almost invisible bottom chord wire bracing.

The rod trusses were inspired by many iconic glass buildings around the world, such as the glass pyramid at the Louvre in Paris, France. Rod trusses were used in the atrium roof where it is a cylindrical form and they form a two-way system. The webs of these trusses in the north-south direction lie in a plane perpendicular to the cylindrical surface of the roof. All bottom chords and diagonals of the rod trusses

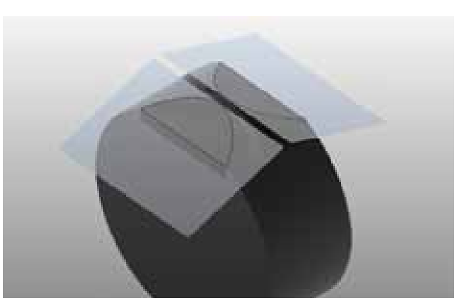

Figure 3. Geometric basis of elliptical truss top chords.

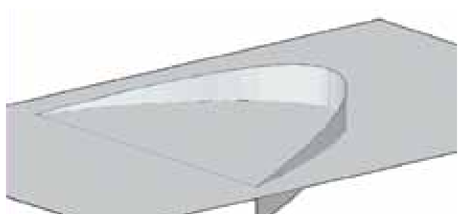

Figure 4. Geometric basis of elliptical truss bottom chords.

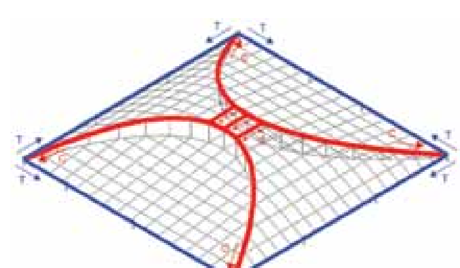

Figure 5. Structural flow of forces in primary roof members.

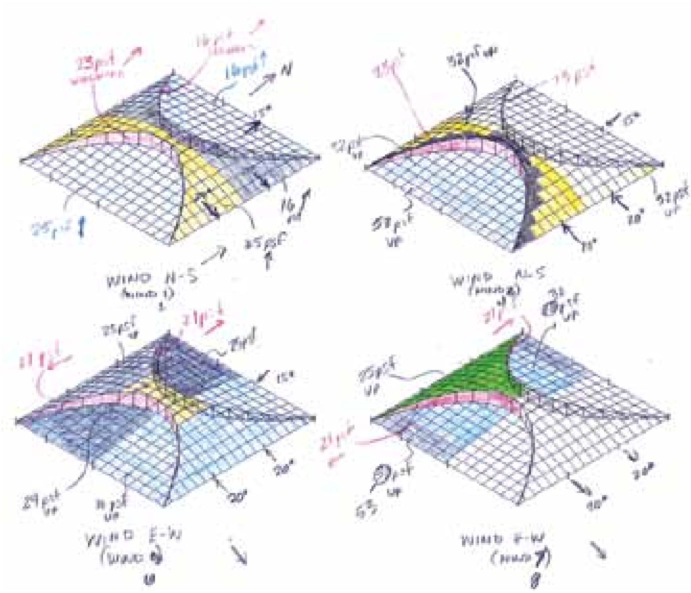

Figure 6. Examples of wind pressure load cases.

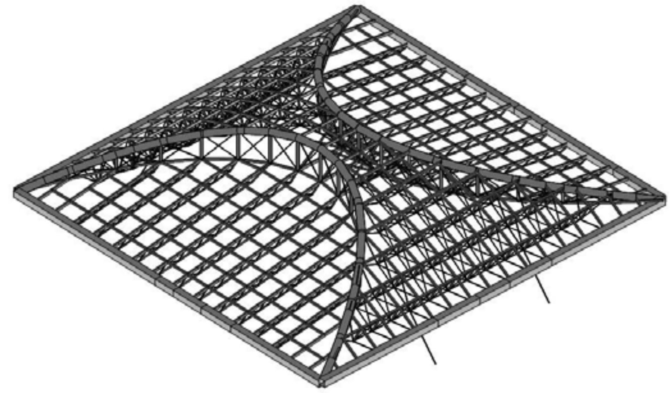

Figure 7. RISA–3D model.

are designed for the predicted compression and tension forces under various unbalanced and uplift load cases, and the depth of each truss varies according to its span. The rod trusses have rectangular HSS top chords to receive the glass roof panels and round pipe verticals. The rods are all reverse threaded to their clevises so no turnbuckles are required. To reduce the compression demand to within allowable limits on the steel rod bottom chords under wind uplift conditions, steel cables anchored to building columns were added in four discreet locations to hold down the field of the curved rod trusses.

A ring beam consisting of an HSS18x18 resolves the thrust from the elliptical trusses in the corners and also resists the minor amount of horizontal thrust from the secondary members. Steel columns support the ring beam vertically at each corner and intermittently around the perimeter. Slotted holes and fixed bearings were carefully arranged around the perimeter of the ring beam to anchor the roof structure for horizontal and uplift loads, and to allow for horizontal movements due to thermal changes and live loads.

Documentation

KPFF chose to document this roof structure in AutoCad 2D, although study models in Revit, Sketch-Up, and AutoCad 3D were utilized. Conventional plans, sections and details were drawn to fully describe the dimensional parameters of the structure. *Figure 8* shows one building section cut through the center of the cylindrical portion of the roof.

Fabrication and Erection

The construction manager, Tarlton Corporation of St. Louis, contracted with The Gateway Company of St. Louis to provide the detailing and fabrication of the atrium roof structure and the associated glass wall steel framing. Gateway had the elliptical pipes rolled out of town and shipped to their fab shop, where they pre-assembled most of the roof structure in their yard to assure good fit up in the field.

The steel erector for the entire building, including the atrium roof structure, was Ben Hur Construction of St. Louis. In order to safely

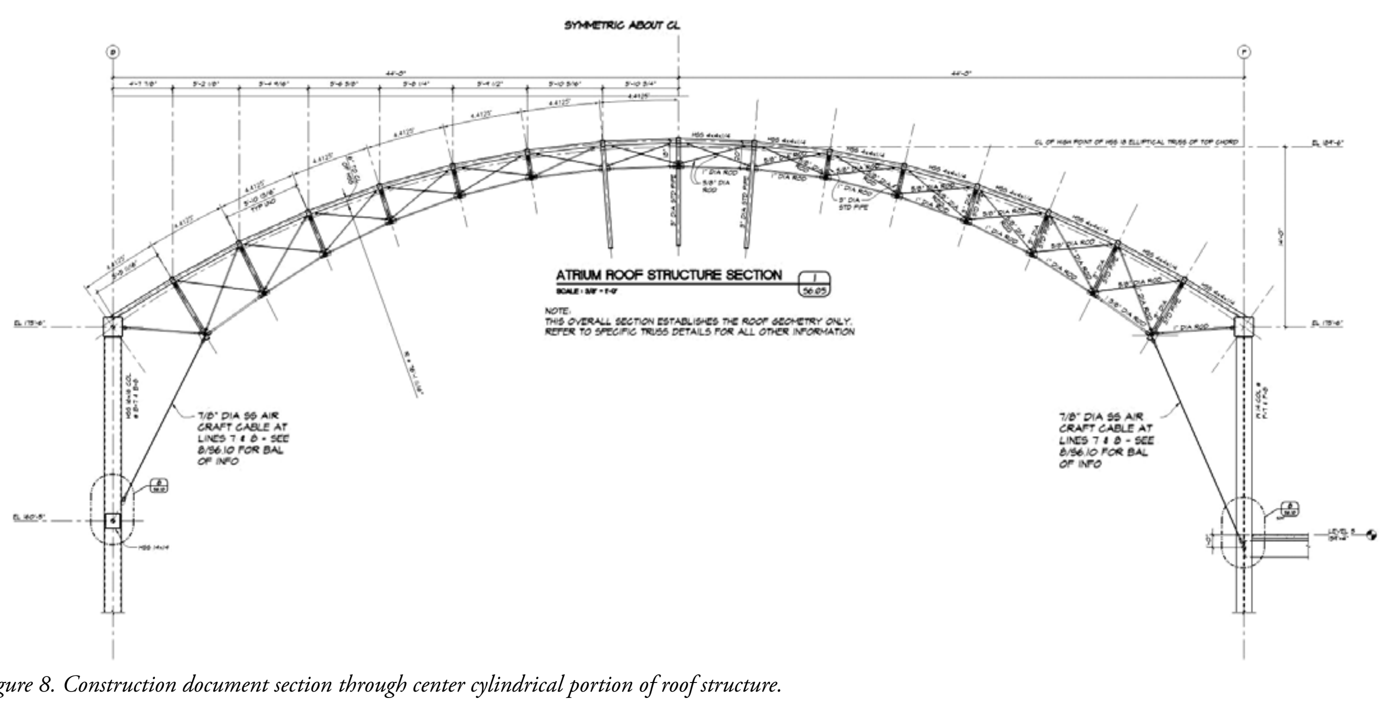

Figure 8. Construction document section through center cylindrical portion of roof structure.

Figure 9. Roof pre-assembly at fabricator's yard.

Figure 10. Temporary work platform during roof erection.

erect the atrium roof steel, along with facilitating roof glazing, sprinkler piping, field painting, and electrical work, Tarlton and Ben Hur chose to build a temporary work platform just below the roof structure. The scaffold for this platform extended some 65 feet down through the atrium floor openings below, and was a significant structure in and of itself. It also proved to be an invaluable benefit to provide access for inspections of the structure.

Gateway and Ben Hur collaborated and separated each of the elliptical trusses into three sections to stay within the tower crane's load capacity. Due to careful planning, the atrium roof structure was erected quickly in a little over one month.

Project Team

Owner: Washington University in St. Louis
Structural Engineer: KPFF Consulting Engineers, St. Louis
Architect of Record: Moore Ruble Yudell Architects & Planners, Santa Monica, CA
Associate Architect: Mackey Mitchell Associates, St. Louis
Construction Manager: Tarlton Corporation, St. Louis
Steel Erector: Ben Hur Construction, St. Louis
Fabricator: The Gateway Co., St. Louis

Conclusion

By listening to and embracing the artistic goals and visions of the architect, a structural engineer can provide valuable feedback and input into an artistic pursuit. The Olin Business School was a project in which the structural engineer was able to take an active artistic role in developing a striking work of structural art in terms of efficiency, economy, and elegance in the atrium roof structure. The soaring and dynamic atrium roof structure has become the architectural centerpiece of Knight Hall and Bauer Hall.▪

John P. Miller, P.E., S.E., is one of the founding principals of the St. Louis office of KPFF Consulting Engineers. John can be reached at ***john.miller@kpff.com****.*

Marc A. Friedman, P.E., S.E., is an Associate at KPFF Consulting Engineers' St. Louis office. Marc can be reached at ***marc.friedman@kpff.com****.*