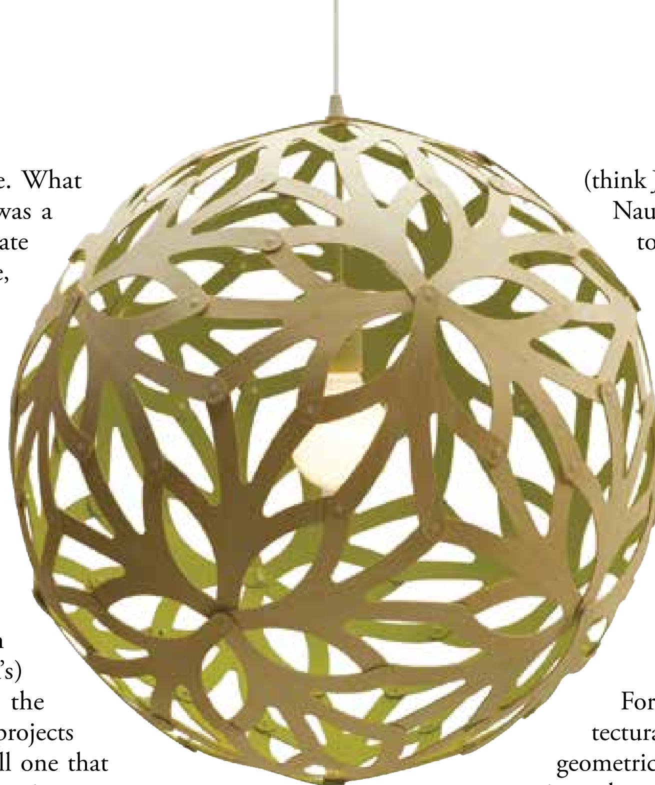

Figure 1. Sphere lampshade inspiration. Courtesy of David Trubridge Studio.

Amazon Spheres

An Uncompromised Vision

By Jay Taylor, P.E., S.E., and Robert P. Baxter, P.E., S.E.

Imagine your ideal office space. What does it look like? What if it was a sanctuary from the chaos of corporate office life and allowed you to recharge, relax, and be inspired at any time in the day without having to venture outside the heart of the city? This is precisely the kind of space Amazon was dreaming about for their new headquarters campus in Seattle, Washington. Doing away with drab and uninspired, The Spheres are a one-of-a-kind workspace that fuse nature into the corporate world. On a recent visit to the site, Jay Taylor, Magnusson Klemencic Associates' (MKA's) Structural Managing Principal on the project, commented that, of all the projects he has designed, he could not recall one that exceeded such challenging expectations in every way more so than The Spheres.

At the project kick-off meeting in early 2013, Amazon challenged the team to conceive, design, and execute a Seattle landmark destination for locals and tourists alike. John Savo, NBBJ's Principal-in-Charge on the project, shared the owner's challenge to the team: "no compromise on vision." Based on comments from the owner, Amazonians, and visitors since the opening, the design and contractor team rose above the challenge.

Vision

Originally referred to as the "Center of Energy," the Spheres were envisioned as a place where Amazonians could "get away from the city" without leaving the neighborhood. A retreat from the day-to-day activity, commotion, and noise of the typical office environment, this "alternative" workspace would provide employees a place to be energized.

The idea of a workspace surrounded by living plants evolved from the concept of a traditional conservatory into a "centerpiece" project embracing the belief that biophilic design – the incorporation of nature into the built environment – would have a positive effect on employees. The lead design principal for NBBJ, Dale Alberda, articulated his vision for the project as a modern interpretation of Victorian conservatories. He wanted a building that had a fully integrated façade structure, with exposed and expressive joints, details, and connections – the structure should be visible and beautiful. "Steampunk" (think Jules Verne's Victorian futurism and the Nautilus submarine) was a term Dale used to describe the aesthetic, and it became a source of inspiration for what the architectural character, structure, and structural details might look like.

Dale also made it clear that the team's goal was to develop a "never-been-done-before" approach for the structural system to create the domes. The design needed to be organic, crystalline, and snowflake-like with an indiscernible repeating pattern or "kit of parts."

Exploration

For several weeks the team studied architectural and structural precedents as well as geometrical and mathematical theories for defining spheres and shell structures. The design team found their solution in, of all things, a lampshade! (*Figure 1*) A team member had seen a spherical lampshade comprised of what appeared to be a repeating organic pattern. Another member of the team identified the pattern as being based on a Catalan solid. The theory of Catalan solids was developed by Eugene Charles Catalan, a French and Belgian mathematician in the late 1800s.

Inspired, the design team dug in. They explored multiple possibilities and ultimately settled on a sphere shape characterized by 60 equally sized and shaped pentagons arrayed around a sphere (technically, a 60-faced, dual-polyhedron Catalan solid, otherwise known as a pentagonal hexecontahedron).

From a structural engineering perspective, MKA was intrigued by the repetition of the pentagon shape and its potential efficiency as a "kit-of-parts solution." However, what intrigued and inspired NBBJ and the design team was the endless possible configurations of steel framing that could be placed within each pentagon and the resultant unique, organic character, making The Spheres a completely one-of-a-kind structure. After literally exploring hundreds of options (*Figure 2*), the team decided on a framing configuration described as looking like a "fighter jet." When the configuration was inserted into each pentagon and arrayed around each sphere, it created the beautiful, organic pattern Dale Alberda had imagined. The client loved the concept – now, how to make the design a reality?

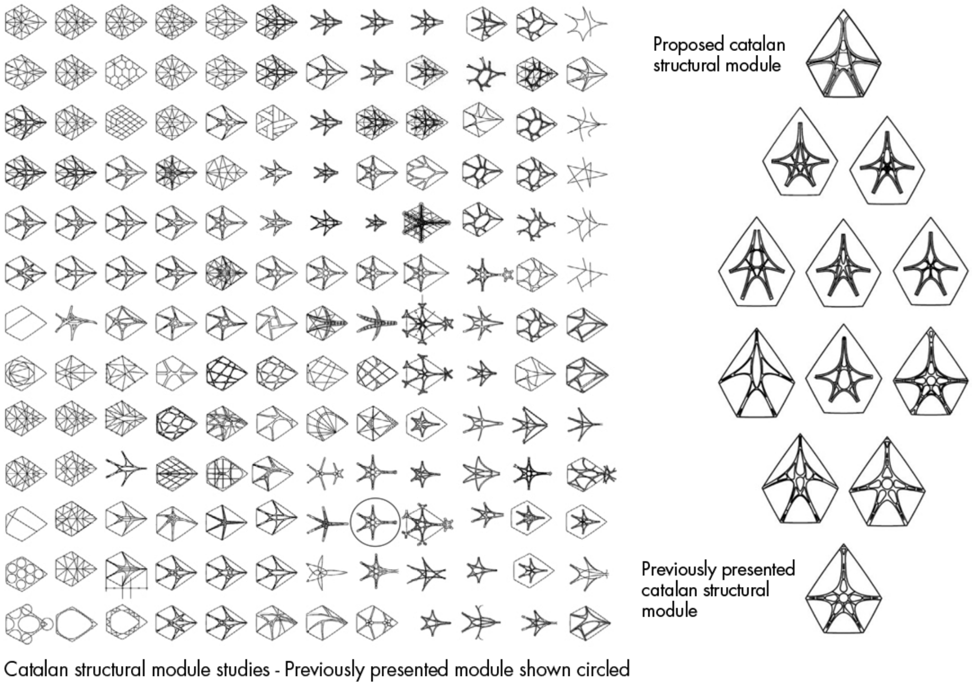

Figure 2. The evolution of the Catalan design.

Designing the Structure

To turn vision into reality, the design team needed to meet several critical goals beyond aesthetics: determine a consistent structural form to enhance constructability and develop a structural analysis methodology for this complex shape.

Establishing a Buildable Geometry

The team coined the term “Catalan” to describe the selected pattern within each pentagon. The original Catalan pattern consisted of rectangular box sections curved in both directions at continuously varying curvatures and twisted about their axis – the shape was reasonable for a model generated as part of an architectural study, but challenging and expensive to fabricate, as it required the entire structure to be fabricated from built-up steel plate boxes. One of the first tasks was to engage the experience of the steel fabricator and steel detailer to understand the boundaries of bending typical Hollow Steel Sections (HSS). Once the boundaries were understood, the design team was able to subtly modify the Catalan geometry such that simplified HSS sections could be rolled into a few constant curvatures without warping. By minimizing the extent of the warped sections and simplifying the HSS sections, the design team was able to simplify fabrication significantly.

MKA created a detailed analysis model directly derived from the Architect’s geometric surface model using the parametric software Rhino/Grasshopper. A single steel Catalan was carefully constructed in the program; then the parametric design tools were used to replicate that Catalan across the entire surface of each sphere. Once the model was fully assembled in Rhino, the geometry was exported to the analysis software along with member sizes and orientations. Then the supplementary façade support elements were generated by a similar process and exported to the analysis model (*Figure 3*).

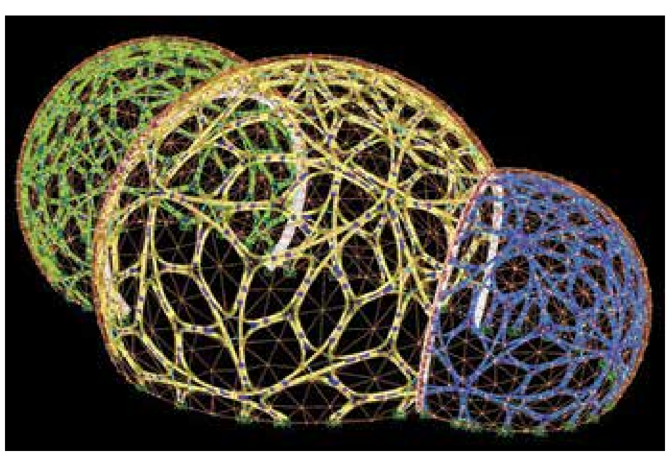
Figure 3. MKA’s analysis model.

Structural Analysis

To test the structural integrity of the Spheres, the team engaged several specialty consultants. The wind and snow consultant, RWDI, provided multiple load combinations with various load patterns across the surfaces of the Spheres. The Rhino model was used to organize each of the thousands of façade elements to wind and snow loads for each load case. The loads were then directly exported to the analysis model with zero manual-data-entry required.

Per prescriptive code requirements, the steel frame of the Spheres necessitates fireproofing. Faced with using either bulky spray-applied fireproofing or expensive intumescent paint, MKA worked with the fire consultant to develop a performance-based fire case to demonstrate how the highly repetitive framing did not require fireproofing to meet the required performance objectives. Hundreds of analysis cases were run varying the zone of framing where the design fire would occur, thereby weakening the structure. In each of these cases, the framing was able to resist the fire load case per AISC-360, *Specification for Structural Steel Buildings*. The result? Intumescent paint was needed only on non-redundant structural arch elements, saving money and delivering the architect’s vision for delicate expressed structural steel.

A large displacement analysis method was used to ensure the analysis captured any second-order effects due to structural movement. This required all load combinations to be run separately. With a model composed of approximately 16,000 frame elements, after optimization, the 96 primary load cases could be run in about 20 minutes.

In addition to typical axial and bending design checks, consideration of two additional effects was necessary. First, the axial force in the curved side plates changes direction as the member curves, and a perpendicular resisting force is required. This perpendicular force causes twist, which must be considered. The second effect was the application of load at the sidewalls of the HSS by connecting elements, which also caused twist.

The along-member stresses were combined with perpendicular stresses due to twist to verify the member design. This was checked at all section corners and the middle of all faces, for each load case. Overall, the design of the structure required tens of millions of stress checks.

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The Final Structure

With a clear vision, an established design, and a vetted structural model, the design and contractor team engaged in the process of final detailing, fabrication, and construction (*Figure 4*). A major contributing factor to the Spheres' success was the team's highly collaborative process throughout the project – especially the early collaboration with the steel erector/fabricator. This early engagement with the steel erector helped determine the detail and splice locations for fabricating the largest transportable pieces in the shop, which ultimately sped up the on-site erection with 620 tons of steel erected in a mere 6 weeks!

The integrated design team workflows were exceptionally efficient, requiring only 18 sheets of structural drawings for the Catalan structural steel! Also, extensive use of jigs during fabrication and component assembly contributed to the creation of a "kit of parts." All assembled Catalans were laser-scanned before leaving the fabrication shop. Survey targets were installed on all members before erection, and installed positions were confirmed before temporary connections being replaced by fully welded connections. The final erected steel was within one thirty-second of an inch of NBBJ's original 3D model.

The attention to detail by all consultants involved and the contractor team allowed the project team to deliver on Amazon's goals of a unique, never-been-done-before structure. A seemingly impossible challenge – to design and construct a beautiful, iconic, and innovative office space while being cost-efficient. The Spheres are a pristine example of what can be achieved with a clear vision and seamless team collaboration and communication (*Figure 5*).▪

Figure 5. The completed Amazon Spheres. Courtesy of MKA/Michael Dickter.

Jay Taylor is the leader of MKA's Cultural Specialist Group. Jay has had a 4-year involvement on the Seattle Design Commission, is an Honorary AIA Seattle member, and was appointed as Affiliate Instructor at the University of Washington Department of Architecture. (jtaylor@mka.com)

Robert Baxter leads MKA's Advanced Geometry Technical Specialist Team. Robert is one of the firm's most advanced modeling specialists and has designed multiple projects with incredibly complex geometries. (rbaxter@mka.com)

Figure 4. Steel fabrication of the Catalan pieces. Courtesy of NBBJ/Sean Airhart.

Project Team

Owner: Amazon LLC – Seattle, WA
Engineer of Record: Magnusson Klemencic Associates – Seattle, WA
Architect of Record: NBBJ – Seattle, WA
Façade: Front, Inc. – Brooklyn, NY
Contractor: Sellen Construction Company – Seattle, WA
Landscape Architect: Site Workshop – Seattle, WA
Fabricator: Supreme Steel Portland (dba Canron Western Constructors) – Portland, OR
Steel Erector: The Erection Company – Arlington, WA
Mechanical/Electrical/Plumbing: WSP USA – Seattle, WA
Steel Bender/Roller: Albina Co. – Tualatin, OR
Steel Detailer: Angle Detailing Inc. (ADI) – Wilsonville, OR