Aspen Art Museum Roof Structure

Art Museum Aspen

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1. Introduction

The Aspen Art Museum (Figure 1) is located in Aspen, Colorado, USA, a Rocky Mountain ski resort town known for its cultural institutions, and a sister city to Garmisch. The museum was designed by Pritzker Prize winning architect Shigeru Ban with several distinguishing features: a woven composite wood screen set in front of the building envelope; a grand stair that is half exterior and half interior, separated by a glass curtain wall; and a long-span three-dimensional wood truss above the third floor level, covering both interior and exterior space. This paper will focus only on the design and construction of the truss (Figure 2). The building structural engineer of record was KL&A Inc. from Golden, Colorado; specialty truss engineering was provided by Hermann Blumer of Creation Holz and Franz Tschuemperlin of SJB in Switzerland.

Figure 1: Aspen Art Museum north and east elevations

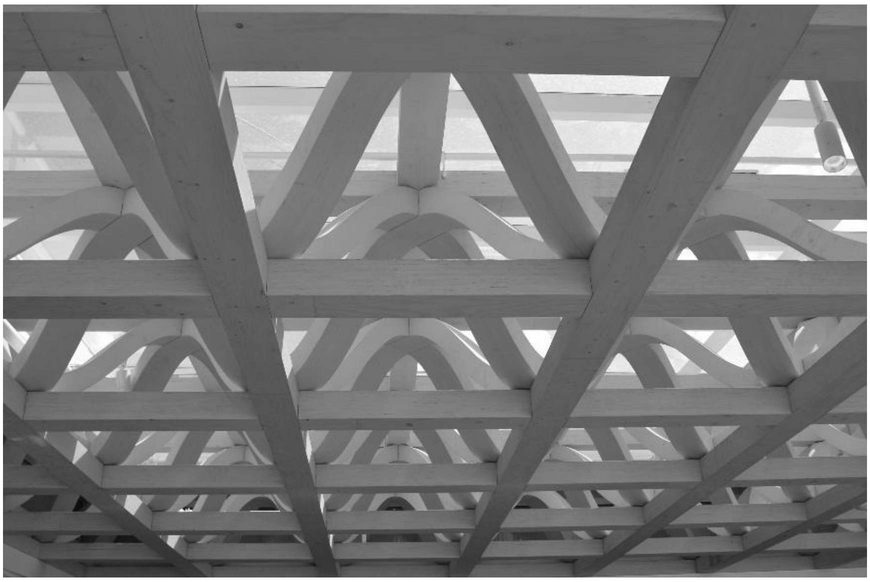

Figure 2: View of the completed space frame

2. Architectural Concepts

The building is 100 ft (30.5m) square with one level below grade and three levels above grade (Figure 3). Strict limits on the total building height set the top of roof at 47 ft (14.3 m) above street level. Ceiling height requirements in the galleries at levels 1 and 2 set the third floor height, leaving a maximum depth of 3 ft (0.9 m) for the wood structure.

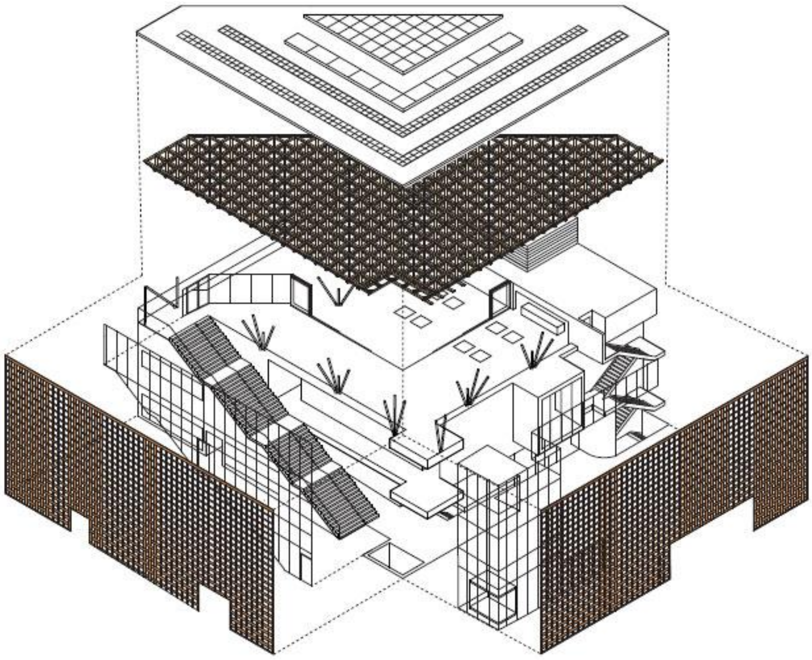

Figure 3: Exploded view of the museum showing the wood truss and columns at the top

The wood truss covers slightly more than half of the roof area, extending from edge to edge of the building plan, and along a diagonal from corner to corner. The truss is supported on a series of two, three, and four-part column clusters, with a maximum span of approximately 50 ft (15.2 m). The truss cantilevers approximately 10 ft (3 m) at the roof edges (Figure 4).

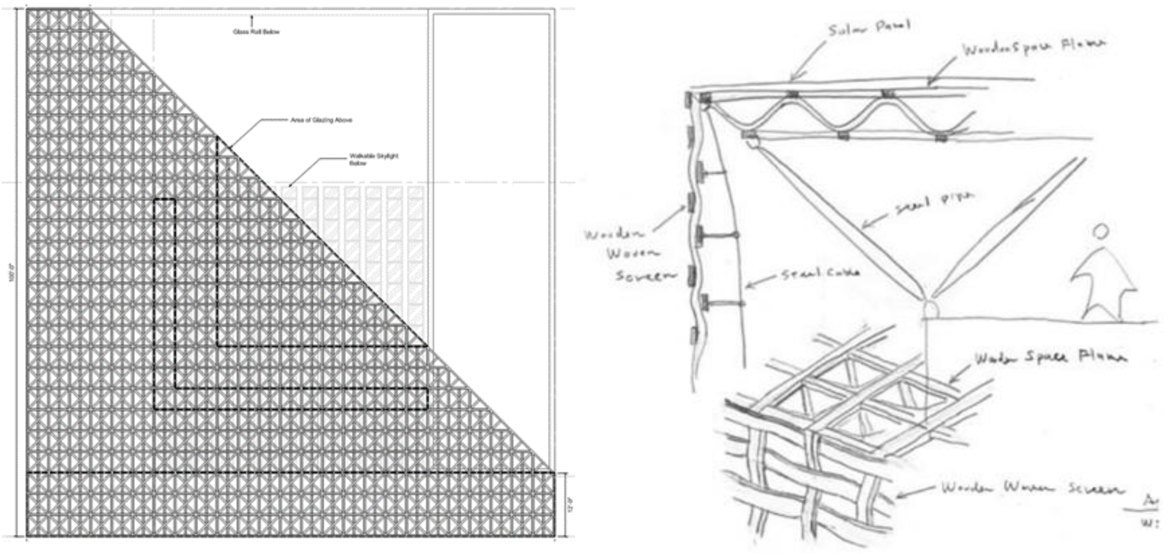

Figure 4: Plan at top of trussand Shigeru Ban’s conceptual sketch

The architect’s concept called for a truss with chords on a 4 ft (1.2m) square grid with top and bottom chords offset by 2 ft (.6m) in each plan direction. Web members were to be of curved wood forming a wave shape that connected to the chords only at tangent points (Figure 4). In addition the architect wanted to minimize the steel components in the truss construction.

3. Structural Design

3.1. Design Criteria

The governing load condition for the truss was the snow load of 83 psf (4 kN/m^2), in conjunction with the strict deflection criteria for sliding glass doors below the truss. Environmental factors include average temperatures from 15°F to 95°F (-9°C to 35°C), average relative humidity from 20% (summer) to 75% (winter), and expected range of equillibriaum moisture content from 4% (summer) to 15% (winter).

3.2. Design Approach

A number of different schemes and connection typologies were evaluated in an effort to solve the unique structural challenges of the truss. It was important to work to the strengths of local fabricators while meeting strict budget requirements. The truss fabricator, Spearhead from Nelson, British Columbia, Canada, worked closely with the structural design team (KL&A, Creation Holz, and SJB) and the architect throughout the design process.

The first challenge of the design was the small structural depth, which resulted in very large chord stresses. To minimize the eccentricity at the chord connection points a half-lap connection type was adopted (Figure 5). This resulted in the chord members occupying the same plane, which was highly desireable architecturally, but also resulted in a reduction in net area at the joints, and local bending stresses at the chord notches. A laminated spruceLVL material – Kerto-S – was chosen for the chord material to provide the required strength. The thicker profile between the half-laps helped improve the members' buckling strength. All chord members are 5 ¼ in deep x 6 ¾ in wide (134 x 171 mm).

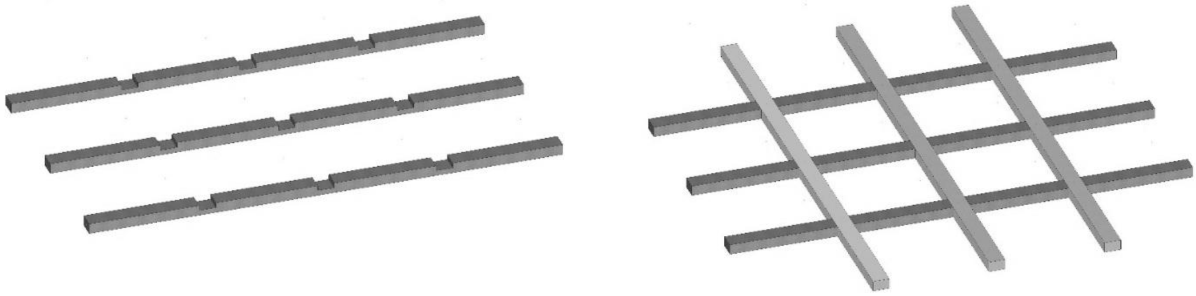

Figure 5: Bottom chords

The curved web members presented greater challenges. The curved shape naturally introduced moments and shears in combination with axial loads expected in a typical truss member. These geometric conditions introduced tension and compression stresses at 45° to the top chord, as well as bending stresses in the half lap region parallel to the top, and shearing stresses at 90° to the top. To address these problems, a custom birch plywood was created with two primary plies alternating with a single ply oriented 90° to the primary plies (Figure 6).The webs were also half-lapped at the joints.

Typical web members are 7 in wide x 4 in deep (178 x 102 mm). The birch plywood was supplied by Koskisen in Finland in sheets 1 ¾ in (45mm) thick, measuring 5 ft x 12 ft (3658mm x 1524mm). To create full width webs, four thicknesses of plywood were laminated together with a pattern of offset splices (Figure 7) that allowed webs of maximum shipping length to be created. The splices in each lamination were 8.5 in (200 mm) long scarf joints. The wood was laminated using a polyurethane adhesive (Purbond HB E452). A steel pin field splice was used to connect webs in the field.

Because of the unique configuration of the web material and expected stresses, a special testing program was conducted in Berne, Switzerland to evaluate the properties of the plywood both parallel to and 45° to the strong axis in accordance with European standards.

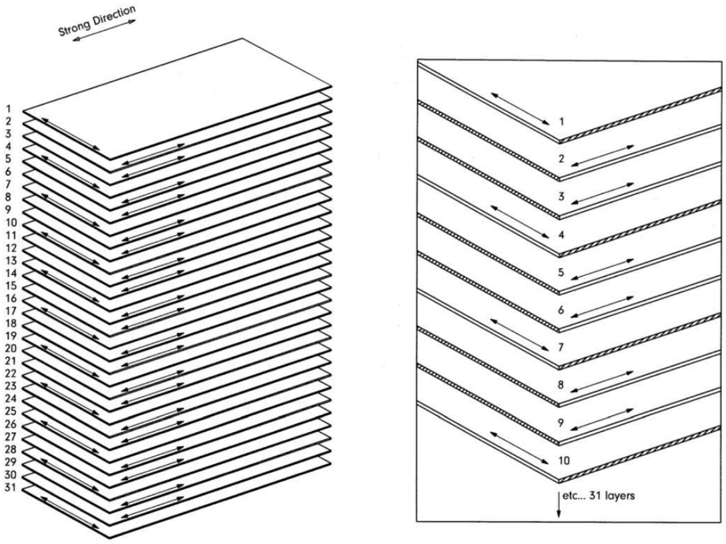

Figure 6: Birch plywood layup

For final construction, the truss was assembled in six layers. First, the two layers of the bottom chords were laid down (Figure 5). Then, full length web members were assembled in two crossing layers with half-lapped joints at every intersection. Web members were screwed to the bottom chord as described in the following. Finally, two layers of top chords were set on top of the webs (Figure 8).

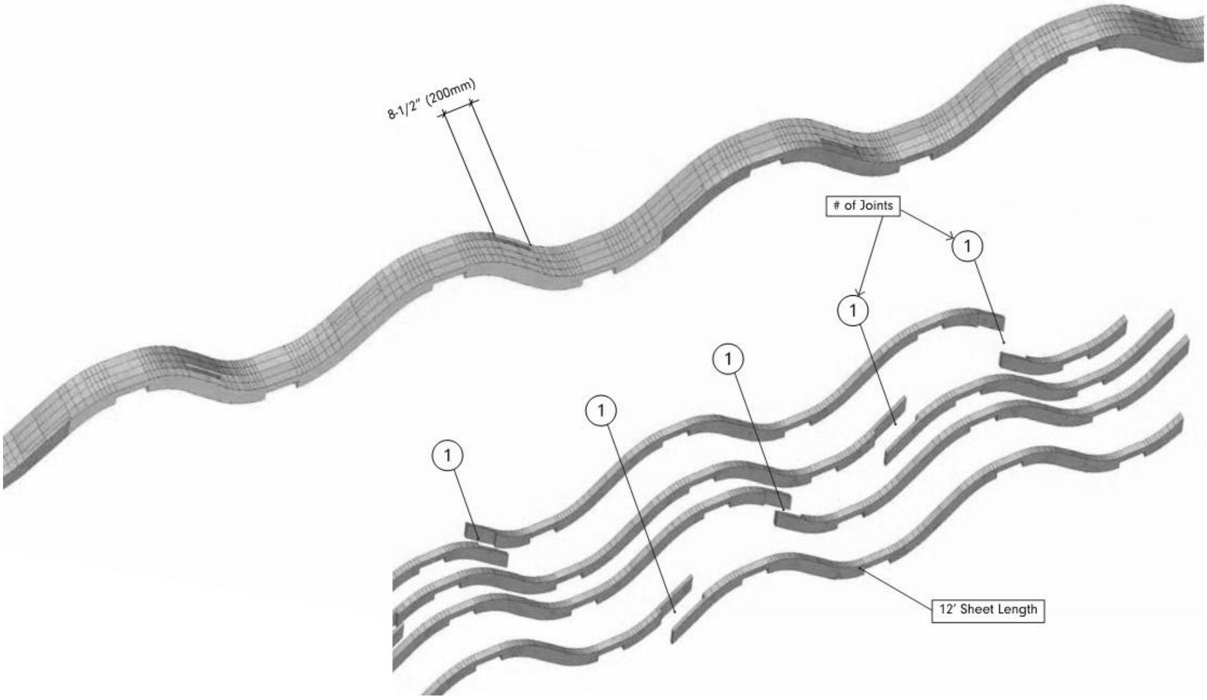

Figure 7: Web splices

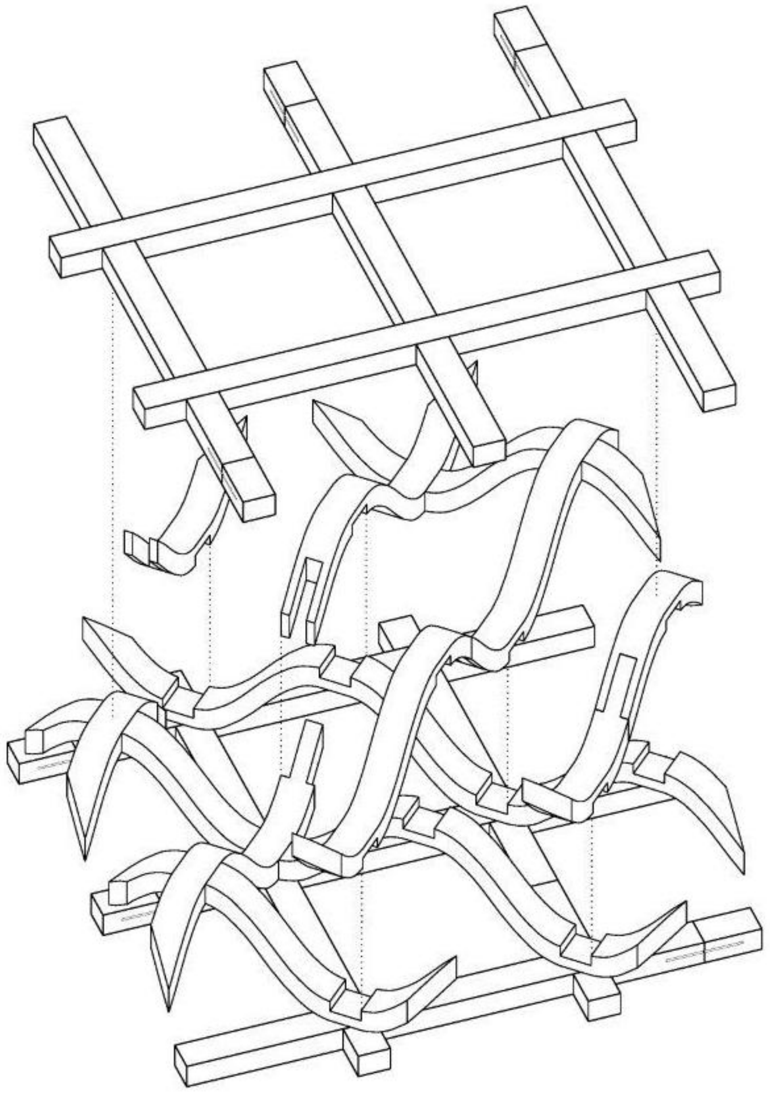

Figure 8: Webs and top chords

Near columns, the typical web size was insufficient to carry the increased shear forces. To accommodate this, the web members were gradually increased in depth up to a maximum of 9 1/8 in (232 mm) over columns (Figure 9).

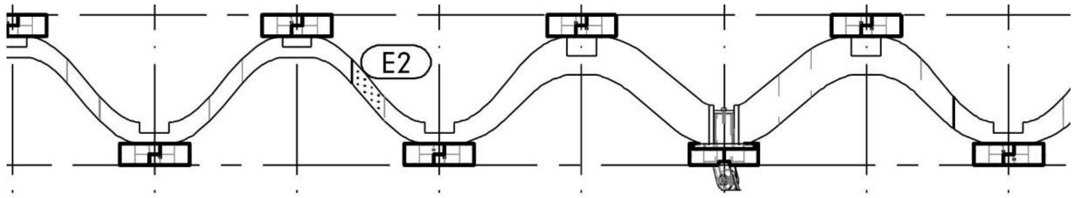

Figure 9. Variation in web member depth to carry high shear at column locations

Typical connections between chord and web members were made with fully threaded SFS WR screws installed diagonally through the joint (Figure 10). Depending on local stresses, connections had as few as 4 or as many as 15 screws. The majority of connections could be formed with screws alone, which was both economical and the preferred approach of the architect. A few top chord joints required strengthening with steel plates set above the chord.

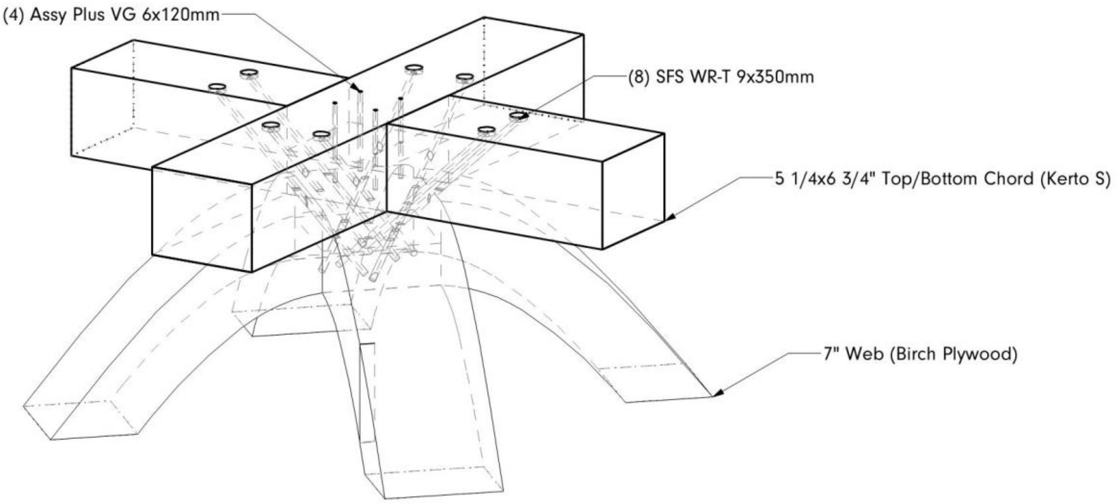

Figure 10: Typical screw connection at chord-web junction

Once the construction sequence and connection typology was established, final structural analysis could be completed. Ultimately, typical member sizes were chosen to control deflections under design dead and snow loads (Figure 11), while increased member sizes and steel reinforcements were used to address local regions of high stress. A continuous edge beam, consisting of two Douglas fir glulams, was introduced along the diagonal edge, to control deflections there. At the architect’s request, this beam was penetrated with a series of holes to lighten its appearance (Figure 17).

Figure 11: Exaggerated deflected shape of the structural model

4. Construction

A single digital model created by Spearhead with direct input from SJB was used to control five different CNC fabrication machines in four facilities. The birch plywood and Kerto chords were manufactured in Finland and shipped to the US. The plywood panels made a stop in New Hampshire where CW Keller made the first cuts for the curved web members (figure 12). All material was shipped to Nelson BC where the four plies of the web members were laminated by hand and cured in a custom-made press (Figure 13). Samples from every gluing operation were prepared and tested for shear strength and cyclic delamination in accordance with AITC standards. All wood was protected with Nano-Perl 119, an ultra thin water repellant coating before being shipped to the site.

Figure12: Web laminations after cutting

Figure 13: Laminations in preparation for gluing (left), and in the custom clamp (right)

The truss was constructed from October to December 2013. Great care was taken to minimize exposure of the wood to snow and water (Figures 14 and 15).

Figure 14: Construction of the truss, showing the bottom chord layer, the web layer, and the top chord layer at each phase of construction.

Figure 15: The finished truss with shoring removed.

5. Conclusion

The Aspen Art Museum opened to the public in August 2014 (Figures 16 and 17) and, as the first major project in the U.S. by Shigeru Ban, was immediately recognized in numerous architectural publications worldwide.

Figure 16: View of the finished truss on opening day - interior

Figure 17: View of the finished truss on opening day - exterior

6. Acknowledgements

The unique structure of the Aspen Art Museum, unprecidented in the U.S., was due entirely to the creative engineering skills of Hermann Blumer of Creation Holz and Franz Tschuemperlin and Benno Behrendt of SJB, combined with the ingenuity and skill of the timber craftsmen at Spearhead in Nelson, British Columbia. While there were many at Spearhead, special thanks go to Ted Hall, Randy Richmond, Geoff Lucas, and Manfred Elmer. The architect of record was Cottle Carr Yaw Architects of Basalt, Colorado.