Making of the Cloud Structure

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Introduction

The cloud structure is an articulated entrance portal to the existing Fashion Show Mall. The main body of the structure has an ellipsoid shape that is 478 feet long, 160 feet wide, and up to 20 feet thick. The main body of the structure sits between 90 and 120 feet off of the ground level. It slopes 12 degrees in the transverse direction and 4 degrees in the longitudinal direction, and its two support columns are set approximately 250 feet apart and approximately 16 feet off of its center longitudinal axis.

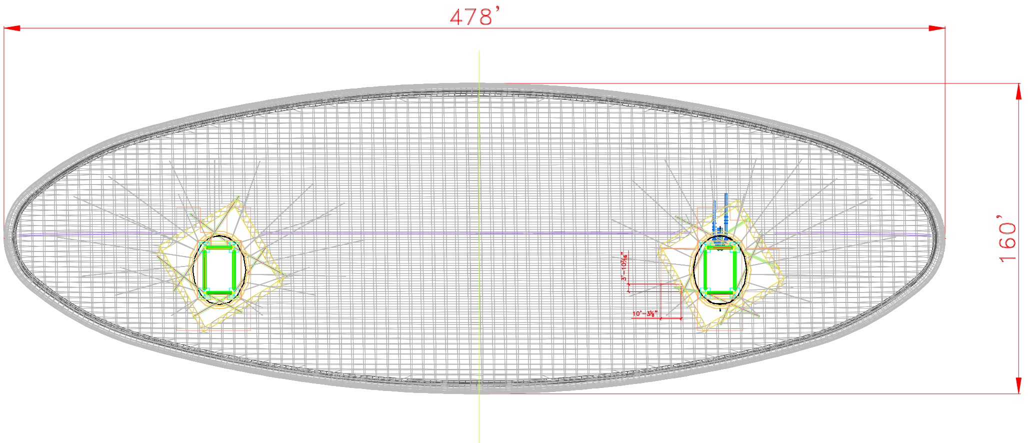

Figure 1. Cloud plan view

The foundations for the new cloud structure penetrate the existing subterranean parking structure at both the Plaza (Ground) level and at the slab on grade below. This required cutting out sections of the existing precast, presressed concrete deck system at the Plaza level as well as the slab on grade below. The new foundations for the cloud were coordinated with the existing concrete column spread footings of the parking structure.

The purpose of the Cloud sign structure is to be an urban marker and accentuate the presence of the shopping center among the nearby casinos. The sign structure in not merely symbolic feature but functional. The cloud sign will provide shade from the sun during the day for a food court below, and by night the structure would act as a large reflective display medium for the projection of images and advertisements.

This paper will discuss the decision making process which ASI used to evaluate the original framing concepts; present the revised framing concepts used for bidding and ultimately for the project; describe the initial installation methodology; and briefly discuss the revised installation procedure used for the Cloud structure. This project was completed in the summer of 2003, at the Fashion Show Mall on Las Vegas Boulevard in Las Vegas, Nevada, USA.

ASI was subcontracted to design the entire structure, and provide fabrication for the space frame and cable elements. During the project the cladding and cladding support framing was modified, and ultimately reengineered by the fabricator of these element.

Original Framing Concepts

The framing concepts for the column towers and foundations were similar to that used in the final design. See below for a description of these elements.

The original bid documents represented a steel truss framing concept for the main body of the cloud structure. See figure 2 for an isometric immage of the original framing concept. Large transverse and longitudinal steel trusses were used to span the main body of the structure to the column supports, with additional help from 36 to 48 steel cables connecting the tower with the steel truss system. The transverse trusses were varied in depth to match the lens-shaped outer profile of the structure. Secondary steel members were used to span between the trusses. This steel truss framing required a structure weight of approximately 23 psf.

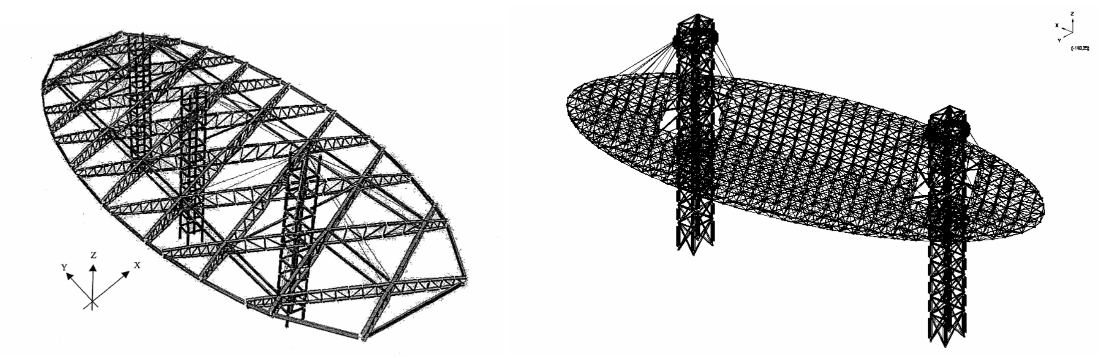

Figure 2: **Original framing concept** **Final framing concept**

Cladding panels attached directly to the steel truss and secondary framing at both the bottom and top surface of the main body. Three steel column towers supported the main truss framing. These column towers penetrated the existing Plaza (Ground) level and were set upon concrete spread footings, which in turn were directly supported by a caliche base.

Final Framing Concepts Chosen

In providing a design/build bid on this project, ASI reviewed the defined framing system and assessed the efficiency. Based on our review, and our experience in designing complex structures, we developed a more efficient framing concept (See figure 2 above for an isometric image of the final framing concept). This revised concept incorporated a space frame that would span between the column towers, with additional support from steel cables. This revised space frame concept dropped the framing weight to approximately 13.0 psf for the space frame and cladding framing. Since the cost of the structure is always dependant on the price of the materials to be included, a significant reduction was achieved in the overall project cost as the result of going to a lighter weight space frame concept. In addition, the assembly and installation of the space frame structure was estimated below that of the original concept, due to the ability to perform much of the activities on the ground, as opposed to in the air.

The space frame consists of a double layer offset triangular grid assembly of individual steel members (struts) joined at their ends through a solid ball node. The space frame module was 10.5’ x 12’ in plan, and 11 feet in depth. The individual struts vary from 2 inch diameter to 6 inch diameter pipes.

In addition, hanging and uplift cables supported the space frame vertically and laterally. These cables, which were attached back to the column towers via added steel support rings, reduced the span for the space frame. A total of 30 upper cables were used. The cables were galvanized steel strand, with bridge spelter sockets at each end. The upper cables varied from 1.5” to 2” in diameter. 16 lower cables were used, 7/8” in diameter, to assist in resisting uplift due to wind. Lateral stabilizing steel struts were provided, horizontally between the space frame and the tower structure. These struts acted to minimize the lateral drift for the main structure.

Since the space frame was designed to be flat in shape, for efficiency of member sizing, secondary framing was needed to achieve the rounded shape required for the outside envelope. The cladding panels were then attached to this secondary framing. ASI designed and detailed the secondary support framing and cladding in our final permitting package. The secondary framing was designed by ASI as Channel members and angles. However, ASI's client decided to have the actual cladding system fabricator design and detail their own specific support system. They then took over the EOR responsibilities for the cladding and support framing. The final secondary framing consisted of light gage Z sections for both vertical and horizontal framing, attaching back to the space frame nodes. The top cladding was galvanized metal decking, and the bottom cladding was 1 foot wide flat aluminum panels that attached directly to the light gage sections.

A support ring truss, surrounding each of the column towers was provided for two reasons. First that it provided a consistent connection point for the cable supports around the tower. Second that it allowed for constant cable support in the installation phase. It was originally decided by the erector that they would assemble the space frame at a low height, in its final inclined position, and jack it into place once assembled. This allowed the cables to be attached to the ring truss, in a lowered condition, so that the ring could be raised to move the space frame into final position. The upper ring truss consisted of wide flange chord members and perpendicular webs, and double angle members as diagonal web components. The upper ring truss was approximately 4 feet in height.

Two steel column towers were used to support the main body framing. These towers, 15' x 23' in plan and up to 220 feet in height, consisted of wide flange verticals and double angle horizontal and diagonal members. All 4 faces of the column towers were framed with the horizontal and diagonal members. The vertical members were W36x230, and the horizontal and diagonal members were double 8x8x1/2 angles. Column cladding frames and perforated aluminum panels were included for the majority of the column height. The frames were oval in shape and connected back to the column tower near the corners. The column cladding frames were 4 feet high and consisted of 6"x6" steel angle chords with 6"x6" vertical and diagonal angles to complete the trusses.

The concrete foundations for the column towers were approximately 60' x 40' in plan and up to 7 feet thick. These sat directly on the local caliche layer. The foundations were designed for both bearing and overturning requirements.

Since the Cloud Structure was an exterior application, guttering and drainage systems were required. Gutters were placed integral with the roof decking to take a majority of the water into an internal drain system. However, since the roof was sloped significantly, it was always understood that some of the roof drainage would overrun the structure and be taken care of by the adjacent building roof drains. A system of internal drain piping was installed, hanging from the secondary cladding framing, or in some instances from the space frame nodes. At no time were any loads directly applied to a space frame strut, as they are purely axial load carrying members. Additionally a catwalk system was also installed for portions of the structure. This system ran within the depth of the space frame system, and hung from either the secondary framing or the space frame nodes. This catwalk system was intended for future maintenance access. One access panel was supplied on the lowest area of the underside of the structure, and two access hatches were supplied to the upper cladding surface.

Design of the Cloud Structure

In deciding on a space frame support structure for the ellipsoid shaped, varied depth structure, ASI examined the framing alternatives to enable the space frame to maximize standard part types. In using a space frame system it is most economical if standard part sizes are maintained. Therefore, it became necessary to have a flat space frame shape with the maximum plan dimension for the regular grid and minimal special parts to frame the edges of the ellipsoid shape. A combination of space frame and nosing framing was required to create the desired appearance while minimizing cost.

In examining the alternatives the first step was defining the 3 dimensional geometry of the outer skin and working back from that shape. Based on that review a depth and grid of space frame was determined (approx. 11' deep and a plan grid of approximately 10.5' x 12') and the plan boundary established for the space frame elements. The second step involved analyzing the space frame structure based on the tower support framing locations. Combinations of cable support points were examined to maximize the efficiency of the space frame elements and balance support points with cable assemblies. Based on many model alternatives, the most efficient solution was chosen for cables, support points, and space frame member sizes. The third and final step in the process was providing a final member size and component design for the space frame itself. This involved analysis of the components and an evaluation of part size uniformity to minimize weight while maximizing efficiency during fabrication and installation.

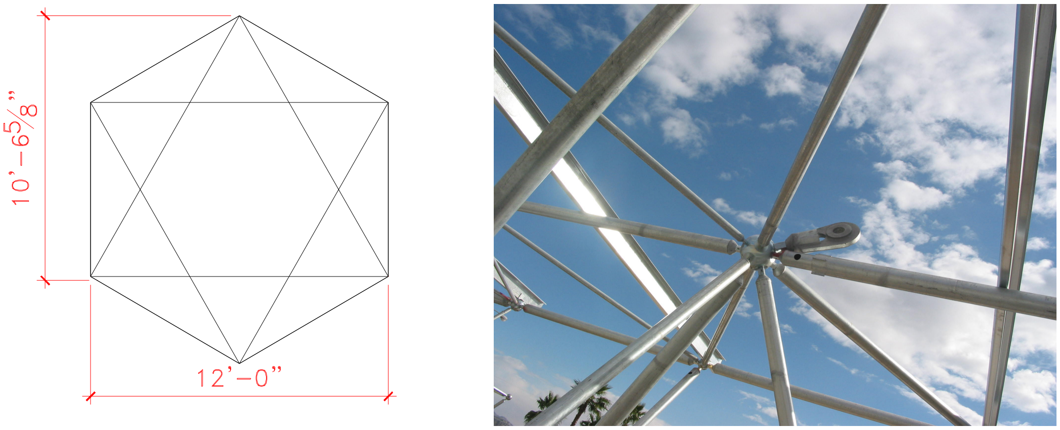

Figure 3. Typical module – plan & typical assembly

Engineering Analysis.

The cloud space frame and the two supporting towers were analyzed using a nonlinear computer program. This allowed for the three-dimensional analysis and design of the space frame elements, the geometric nonlinear cable elements, the connecting strut elements, and the tower elements. Initially a 3-D model was built in Autocad to define the surface geometry and then the space frame node locations. This data was imported into the program, where truss, beam, and cable elements were assigned. The tower connections were pinned to the bottom support foundation.

Truss elements (SF struts, connector struts, and horizontal and diagonal column tower members) are capable of resisting only axial forces. The beam elements (column tower verticals and ring beam members) transfer moments and shear forces at connection joints. The cable elements only carried tension loads. The program uses an iterative non-linear approach to analyze the structure and remove stiffness contribution of cable elements when they become slack. The design loads were computed based on the 1997 edition of the Uniform Building code (UBC) and the wind load were based on a wind tunnel study provided by RWDI for the Owner. The computed design loads are applied at the nodes for the various load cases, due to the nonlinear nature of the structure. Because of the cables, the principal of superposition is not applicable. Hence the load analysis was carried out independently for each load combinations.

Based on the analysis output, minimum member sizing was achieved. ASI then examined possible economies of scale for fabrication and streamlined the sizing based on loads. After initial strut sizing is complete the connections are verified. A typical connection assembly is shown in figure 4. Based on the strut sizes, the nodes are determined. The node sizes then have an impact on the actual strut fabrication lengths. To further provide economy of scale, the nodes are examined for uniformity, and then final strut and node sizes are determined. Table 1 is a summary of list of strut and node types used in the cloud project.

Figure 4. Node Assembly

Strut Type	Description	Qty.
1	2 3/8" O.D	1481
2	3 1/2" O.D	1057
3	4 1/2" O.D	859
4	5 9/16" O.D	269
5	6 5/8" O.D	295
	Total	3961

Node Type	Description	Qty.
1	5" Diameter Ball	299
2	6" Diameter Ball	269
3	7" Diameter Ball	11
4	8" Diameter Ball	300
5	11" Diameter Ball	74
6	14" Diameter Ball	8
	Total	961

Table 1. Summary of list of strut and node types used in the cloud project.

Original Installation Concept

The installation of the foundation, column towers, ring trusses, and cladding elements were similar to that for the final concept. See below for a description of these elements.

Based on the direction of the Erector, and their lifting Engineer, it was determined that the entire main body would be assembled just above ground level on scaffolding and then hoisted in one piece to the final position. The space frame would be assembled in its final inclined positioning. This would allow for the least amount of cost for access lifts and scaffolding costs. The space frame members were to either be assembled on the scaffolding or assembled on the ground and lifted in sections onto the scaffolding. The cladding could also be attached in this low positioning. In this concept, minimal loads would be induced onto the space frame until the cables and connector struts were installed. The use of scaffolding would also ensure the best ability to align the space frame members when they were attached or laced between preassembled sections.

The cables would be attached to the space frame and to the ring beams in this lowered initial position. The struts would also have to be temporarily attached to the space frame and indirectly to the column towers, to maintain the stability of the main body during lifting. The entire assembly would then be jacked or hoisted into its final position, and the ring beam and struts would be provided their final connections. The design of this lifting operation and equipment was to take a major effort, as the loads and conditions were quite demanding.

Modified Installation Procedure

The first item to be completed was the demolition to the plaza deck and the subterranean slab. Next was the forming and pouring of the concrete foundations. Once the foundations had sufficiently hardened, the tower framing was begun. The tower framing was assembled in sections on the ground and hoisted and attached to the section below. This method was used until the topping out of the towers.

The upper ring beams were then brought to the site in 4 pieces. These pieces were then assembled at the base of each column tower. They were then welded together in that location. The ring beams were then hoisted, from points on the tower columns, to their final position and attachments on the tower frame. The cables were then hung from the ring beams.

Figure 5. Segments around the north tower and segments around the south tower

Due to the Erectors problems in designing and fabricating the appropriate lifting frames and equipment in time, a revised erection strategy was decided by the Erector. This new strategy was to pick sections of the space frame and attach them to the cables and tower structure or cables and adjacent space frame. Since this was to be done at the final height, between 90 and 120 feet above the ground surface, no scaffolding or shoring was to be utilized. Since each segment was unbalanced, with respect to its support verses the center of gravity, guy cables were required to stabilize the segments. Since there were severe weight limits for the cranes available, the space frame had to be set in over 40 different segments.

Per the Erectors request, ASI ran analysis models for each segment and stage for the erection. This analysis was required to check that no space frame members were overloaded, to design a guy cable system to stabilize the sections, and verify lifting points within the segments. If any member was found to be overloaded, a detail for strengthening the member was provided. The guy cable system was immensely important as each segment had to align with the adjacent space frame within fractions of an inch in 3 dimensions, to allow the struts to be laced in the air. The overall space frame alignment had to be maintained or the final pieces would not be able to be installed between the existing segments.

As can be seen from the erection photographs figure 5, 6 and 7, the sections were completed around each of the column towers first. This created a stable system of space frame, connector struts, cables, and the tower colums. Once the sections around the column towers were done, the center sections were placed between the column sections. This tied the towers together and formed the main framing support for the rest of the space frame. Then the perimeter end and center sections could be attached, cantilevering off of the main sections.

Figure 6. Connecting the north and south segments

Figure 7. Nose installation and light gage framing

An internal catwalk and drainage system were installed after the completion of the space frame. These systems were supported directly by the secondary framing or from the nodes of the space frame.

Figure 8. Cloud after cladding installation

Once the space frame was significantly complete, the nosing frame sections were installed. Once a significant amount of nosing was installed the cladding framing and cladding was installed. The column cladding frames were installed during the installation of the cladding to the main structure. This process also involved assembling the cladding frames from pieces on the ground at the base of the columns. The frames were then hoisted from the ring beams above into their final connection locations. Cladding panels were then attached to the column cladding frames.

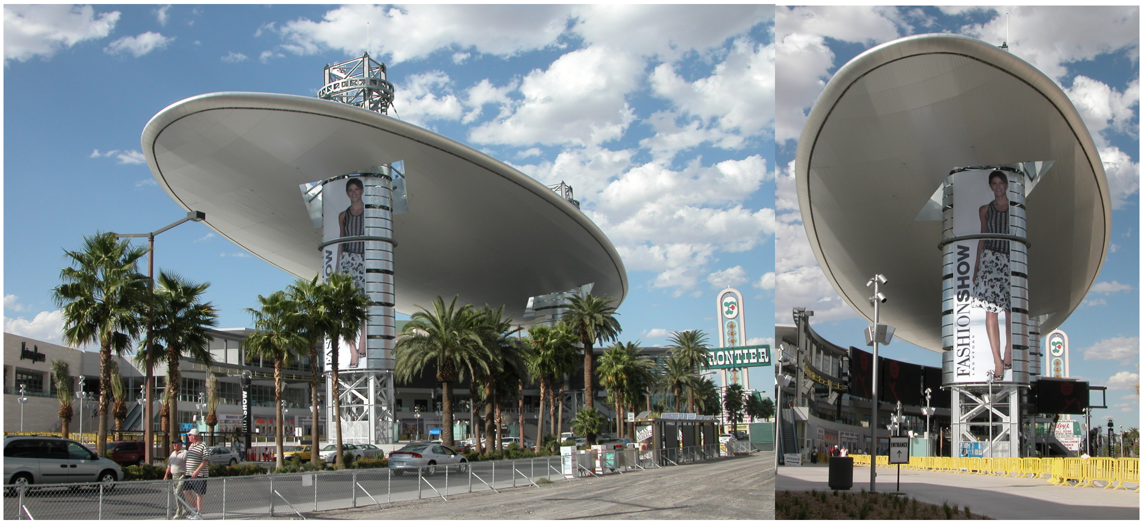

Figure 9. Cloud fully built

Final Remarks

The cloud project is one of the first large-scale cable supported spaceframe projects in the United States, at approximately 60,000 square feet of covered area on each face. There were numerous difficult engineering issues to solve on this problem, with the eccentric cable supported nature of the design. Despite the design difficulty, ASI provided a workable solution for the framing that allowed an efficient space frame solution that resolved the ellipsoid varied depth shape and still resolved the forces at hand.

The final result is a mammoth sized, sleek looking, shade and sign structure that provides visual impact for both the day and night times. The Owner is extremely pleased with the final structure, and is already using it to its full potential.