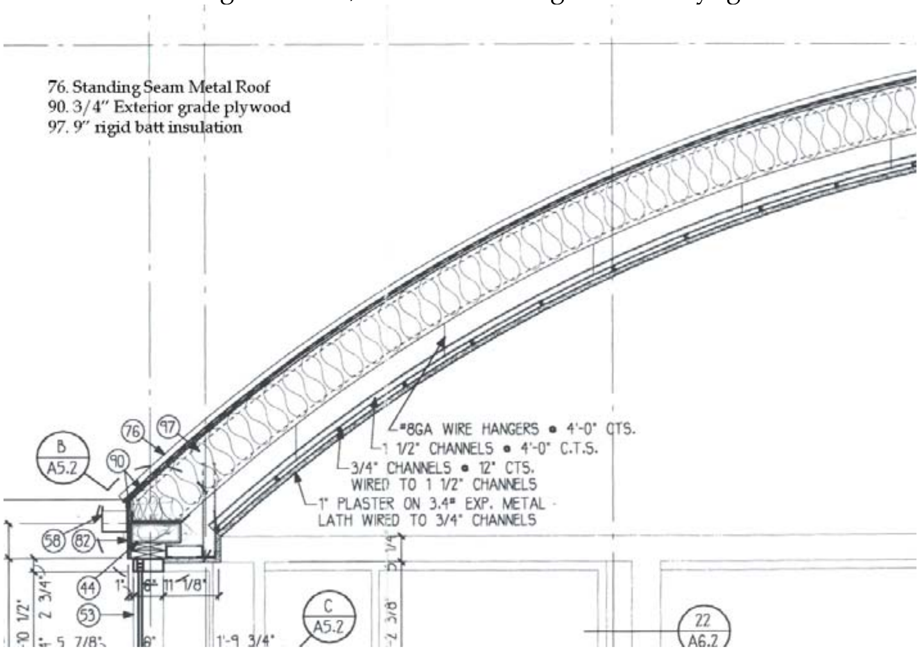
Structural Breadth Work

Introduction

One main focus of the lighting redesign of Louie's was to use daylighting as much as possible during daylit hours to reduce the amount of electric light being consumed in that space. Louie's exterior walls are made up almost entirely with windows which allow a great deal of sunlight to enter and light the perimeter of the space but do not light the interior as well. The interior of the space holds many of the products being sold. To light the interior, and take care of this issue, I decided to add an anidolic parabolic reflector into the domed roof of the structure. This would mean cutting a hole into the dome to accommodate the skylight. I would like to redesign the structure of the dome so that it will be able to hold the weight of the skylight and the existing dead and live loads. I have used Staad Pro and hand calculations to figure out if the members I have chosen will support these loads.

Design Goals

It was very obvious that the roof structure of Louie's needed to be redesigned because of the addition of the anidolic skylight. As the building is standing the roof is made up of a light gage steel system which is prefabricated before coming to the site. The roof structure is designed with a small ring at the highest point of the dome with members spanning around the ring to the base of the dome. A section of the roof can be seen below. The tension ring at the base of the dome is made up of HSS10x4x1/4 which is simply steel tubing. The other materials include a standing seem metal roof, ¾" exterior grade plywood, 9" rigid insulation, #8 gage wire hangers, 1 ½" and ¾" channels, and 1" plaster. With the addition of the skylight, a hole would need to be placed at the top of the dome. This would mean that the structure needs to be redesigned hold not only the live loads and dead loads of the roofing materials, but also the weight of the skylight.



For the roof to be able to accommodate the skylight some new structural components needed to be added to the roof. First of all, a compression ring needed to be added to hold the skylight in place in the roof. Next, I made the decision that I would place eight arched members, equally spaced, around the ring and run from the tension ring at the base of the dome to the compression ring around the skylight. Because of architectural detailing and features of the existing roof, I have chosen to test the same sized steel tubing (HSS10x4x1/4) that is currently being used in the tension ring of the dome for the new members. I will use Staad Pro along with hand calculations to be sure this member type and size will be strong enough to hold the given loads.

Structural Design

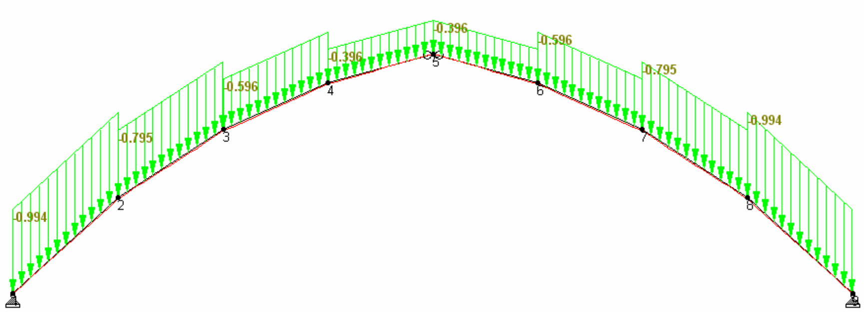
To conduct this analysis I first had to devise a way in which a model could be constructed in Staad Pro. First, using AutoCAD I drew the shape of the dome shape to scale and added the skylight. This would give me the new length of each arched member. I then divided this member into four equal straight sections. Next, I took these lengths and used them to create my model in Staad. After the members were added to the model I placed a pin at the top of the dome to take the place of the compression ring. The forces on the pin will then be converted to forces reacting on the compression ring using simple equations.

After the model was made I needed to calculate the loads on each member. A distributed load would be needed for the live load and dead load of the roof structure and a point load would be needed at the top of the dome to consider the weight of the skylight. The live load used was 30 psf which is a State College requirement for roof design. The dead loads in the roof which the members will need to support are as follows and were found in the Manual of Steel Construction.

Dead Loads	
Material	Weight (psf)
Standing Seam Metal Roof (Aluminum)	3
3/4" Exterior Grade Plywood	3
9" rigid batt insulation	13.5
1" plaster	5
	24.5

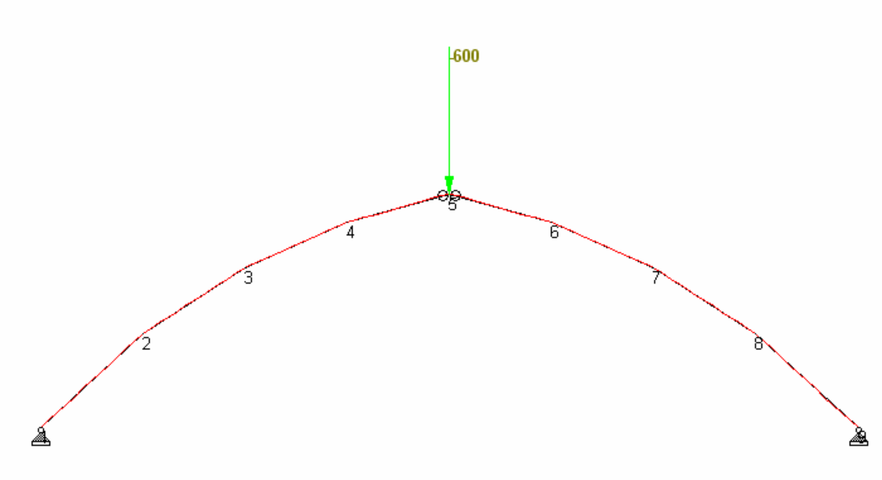
A load combination then needed to be taken into consideration. To do so I used the following equation: 1.2(dead load)+1.6(live load). This resultant load came to 75.2 psf. The distributed load on each section of the arch would not be equal since the distance decreases between the members as you move closer to the top of the dome. The width of the tributary area of each section was taken at the midpoint of each member. Each length was then multiplied by this combination load and loaded onto the appropriate member in Staad. The distributed loads used are listed in the chart below and can be seen in the neighboring screen shot of the loaded members from Staad.

Member		Loads
Designation	Length (ft)	Combination Load (lb/ft)
1	5.27	396.30
2	7.93	596.34
3	10.57	794.86
4	13.22	994.14



The final load which needed to be taken into consideration was the weight of the skylight on the structure. The skylight is made of a reflector material called Miro1 by Alanod. This material is made of 99.99% pure aluminum and is extremely lightweight. The actual skylight was not constructed, so assumptions about its weight had to be made. The reflector itself is made up of approximately 100 square feet of Miro1 aluminum reflector material.

Aluminum used in construction is said to be around 3 psf. To be conservative and be sure a roof was designed to hold this skylight I decided to use a weight of 5 psf to take into account any other materials needed to construct the skylight. After being multiplied by 1.2, the resulting load came to 600 pounds, and was placed at node five. This load case can be seen below.

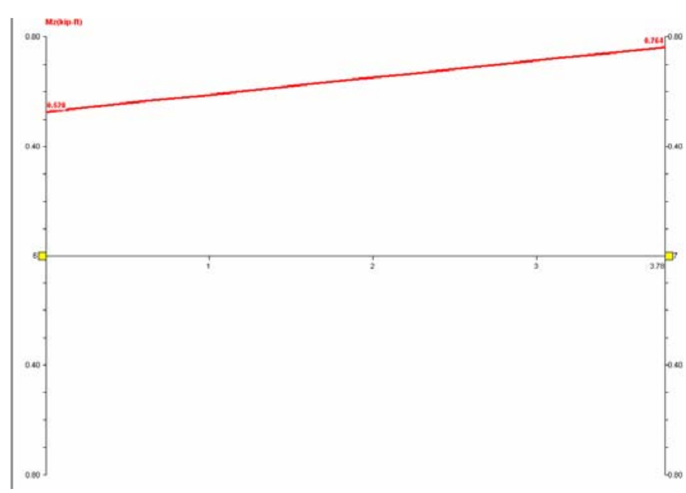


The Staad output for the forces in each member are:

All / Summary / Envelope

Beam	L/C	Node	Fx lb	Fy lb	Fz lb	Mx kip-ft	My kip-ft	Mz kip-ft
1	1 MEMBER 1	1	13619.567	3259.081	0.000	0.000	0.000	0.000
		2	-10461.629	180.159	0.000	0.000	0.000	7.231
	2 SKYLIGHT	1	590.522	-134.939	0.000	0.000	0.000	0.000
		2	-590.522	134.939	0.000	0.000	0.000	-0.634
2	1 MEMBER 1	2	10337.243	1618.503	0.000	0.000	0.000	-7.231
		3	-8573.936	1130.951	0.000	0.000	0.000	8.233
	2 SKYLIGHT	2	604.920	-31.558	0.000	0.000	0.000	0.634
		3	-604.920	31.558	0.000	0.000	0.000	-0.764
3	1 MEMBER 1	3	8645.669	209.377	0.000	0.000	0.000	-8.233
		4	-7737.822	1851.745	0.000	0.000	0.000	5.129
	2 SKYLIGHT	3	602.517	62.426	0.000	0.000	0.000	0.764
		4	-602.517	-62.426	0.000	0.000	0.000	-0.528
4	1 MEMBER 1	4	7921.683	-741.479	0.000	0.000	0.000	-5.129
		5	-7537.175	2113.023	0.000	0.000	0.000	0.000
	2 SKYLIGHT	4	587.682	146.811	0.000	0.000	0.000	0.528
		5	-587.682	-146.811	0.000	0.000	0.000	0.000
5	1 MEMBER 1	5	7537.175	2113.024	0.000	0.000	0.000	0.000
		6	-7921.683	-741.480	0.000	0.000	0.000	5.129
	2 SKYLIGHT	5	587.682	-146.811	0.000	0.000	0.000	0.000
		6	-587.682	146.811	0.000	0.000	0.000	-0.528
6	1 MEMBER 1	6	7737.822	1851.745	0.000	0.000	0.000	-5.129
		7	-8645.669	209.377	0.000	0.000	0.000	8.233
	2 SKYLIGHT	6	602.517	-62.426	0.000	0.000	0.000	0.528
		7	-602.517	62.426	0.000	0.000	0.000	-0.764
7	1 MEMBER 1	7	8573.936	1130.953	0.000	0.000	0.000	-8.233
		8	-10337.242	1618.501	0.000	0.000	0.000	7.231
	2 SKYLIGHT	7	604.920	31.558	0.000	0.000	0.000	0.764
		8	-604.920	-31.558	0.000	0.000	0.000	-0.634
8	1 MEMBER 1	8	10461.628	180.158	0.000	0.000	0.000	-7.231
		9	-13619.566	3259.084	0.000	0.000	0.000	0.000
	2 SKYLIGHT	8	590.522	134.938	0.000	0.000	0.000	0.634
		9	-590.522	-134.938	0.000	0.000	0.000	-0.000

The forces that I am interested in are the forces in the X- and Y- direction at node 5. The total force in the X-direction at this point is 8.1 kip in compression. The total force in the Y-direction is 2.3 kip, also in compression. These forces need to be converted into axial forces so they can be compared to maximum forces the members can actually hold. The angle of the top member, and therefore the angle the axial force must be acting is 15.7°. When the forces were placed head to tail, the angle of the resulting force actually came out to be acting at 15.5° which makes the actual axial force so close to the resultant force and therefore equal to $\sqrt{(8.1^2+2.3^2)}$= **8.4 kip**.



It was also important to be aware of the maximum moment in the member. The maximum moment was found in nodes 3 and 7 and is equal to **0.764 kip-ft**. Here you can see the graph output for the sixth beam.

To prove that the member I have chosen is adequate to hold the weight of the skylight I conducted the following hand calculations. The member values and capacity equations used were found in the Manual for Steel Construction.

FLEXURAL

$$\phi_b M_n = \phi Z_x F_y = (0.90)(50\text{ ksi})(19\text{ in}^3) = 855\text{ kip}\cdot\text{in}$$

$$855\text{ kip}\cdot\text{in}\,(\text{ft}/12\text{in}) = \boxed{71.25\text{ kip}\cdot\text{ft}}$$

$$\boxed{71.25\text{ kip}\cdot\text{ft} >> 0.764\text{ kip}\cdot\text{ft}}$$

AXIAL

$$\phi P_n = \phi A_g F_{CR}$$

$$F_{CR} = \left(\frac{0.877}{\lambda_c^2}\right) F_y$$

$$\lambda_c = \frac{KL}{\pi r}\sqrt{\frac{F_y}{E}}$$

① DETERMINE CRITICAL SLENDERNESS

KL = L SINCE MEMBER IS PINNED AT BOTH ENDS

$$\frac{KL}{r_x} = \frac{16.39\text{ft}(12\text{in}/\text{ft})}{3.48\text{ in}} = 56.52$$

$$* \frac{KL}{r_y} = \frac{16.39\text{ ft}(12\text{in}/\text{ft})}{1.7\text{in}} = \underline{\underline{115.69}}$$

② THE SLENDERNESS IS THEN DEFINED AS:

$$\lambda_c = \frac{KL}{\pi r}\sqrt{\frac{F_y}{E}} = \frac{115.69}{\pi}\sqrt{\frac{50}{29{,}000}} = 1.529$$

③ SINCE $\lambda_c > 1.5$ THE CRITICAL STRESS IS GIVEN AS

$$F_{CR} = \left(\frac{0.877}{1.529^2}\right)(50) = 18.75\text{ ksi}$$

④ THE CAPACITY OF THE MEMBER

$$\phi P_N = \phi A_g F_{CR} = (0.85)(6.17\text{ in}^2)(18.75\text{ ksi}) = \boxed{98.35\text{ kips}}$$

$$\boxed{98.35\text{ kips} >> 8.4\text{ kips}}$$

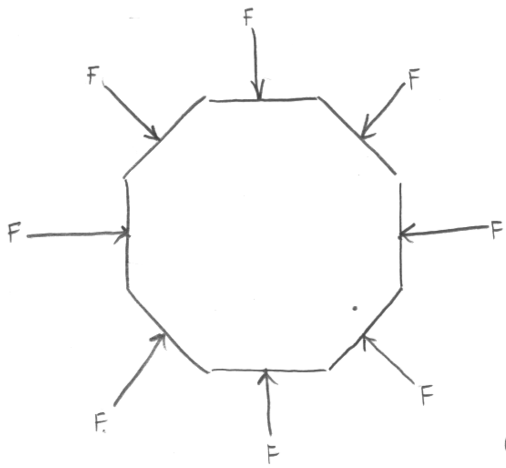
INTERACTION

$$\frac{P_u}{\phi P_n} = \frac{8.4\text{ kip}}{98.35\text{ kip}} = 0.09 < 0.2 \rightarrow \frac{P_u}{2\phi P_n} + \frac{M_u}{\phi_b M_n} = 1.0$$

$$\frac{8.4}{2(98.35)} + \frac{0.764}{71.25} = \underline{0.05 < 1.0}$$

These values all prove that the member size I have chosen is oversized, but will work for this application. The use of this size member will work best with the existing structure that will remain, as well as the architectural detail.

The next part of the design was to be sure this member size would be adequate for the compression ring as well. The compression ring, because of the tight radius and member size, will be made up of eight sections of pipe to form a ring and will fit around the skylight to hold it in place. The equation shown below in the calculation was found in Structural Engineering Handbook by Edwin H. Gaylord.



P_{R1} = compressive force in ring section

N = number of ribs = 8

F = Horizontal force from member

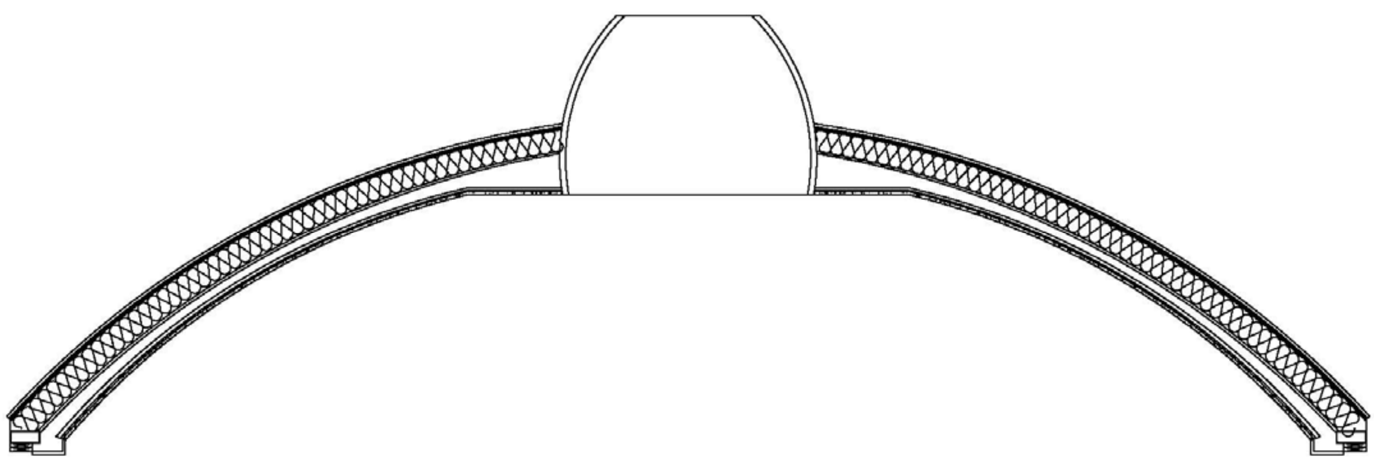
$$P_{R1} = \frac{F_1 \cot \gamma_1}{2\sin(\pi/N)} = \frac{F}{2\sin(\pi/N)}$$

$$P_{R1} = \frac{8.1\text{ kip}}{2\sin(\pi/8)} = 10.58\text{ kip}$$

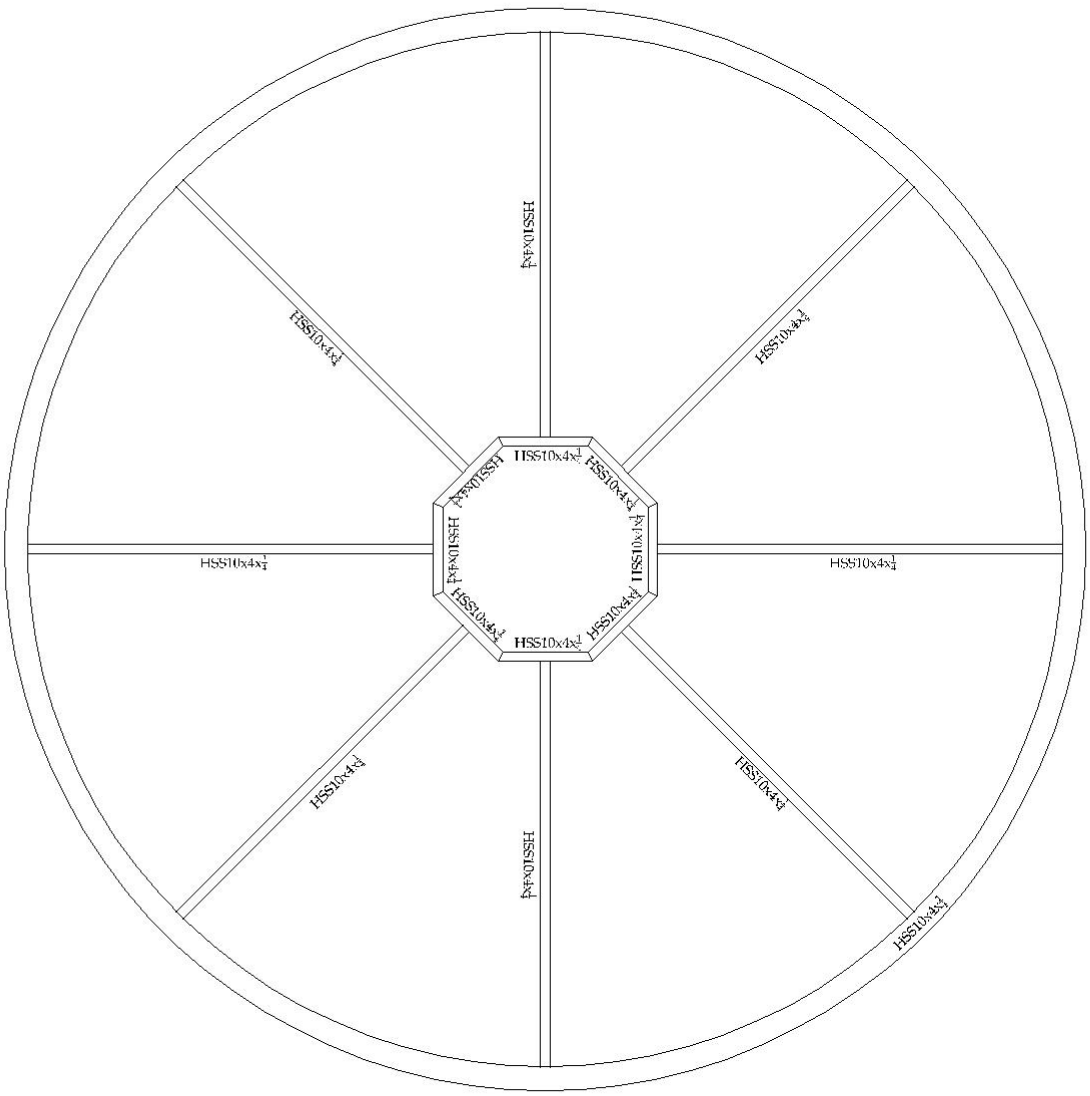
Capacity (from calc above) = 98.35k

$\boxed{10.58\text{ k} < 98.35\text{ k}}$ ✓ok.

Roof Section



Roof Plan



Conclusions

From the STAAD analysis and the hand calculations I have proven that the roof system I have designed will not only be able to support the inevitable dead and live loads, but the skylight as well. The member size I have chosen is oversized but makes the most sense based on the materials used in the original roof design, and on the architectural detailing of the existing roof.