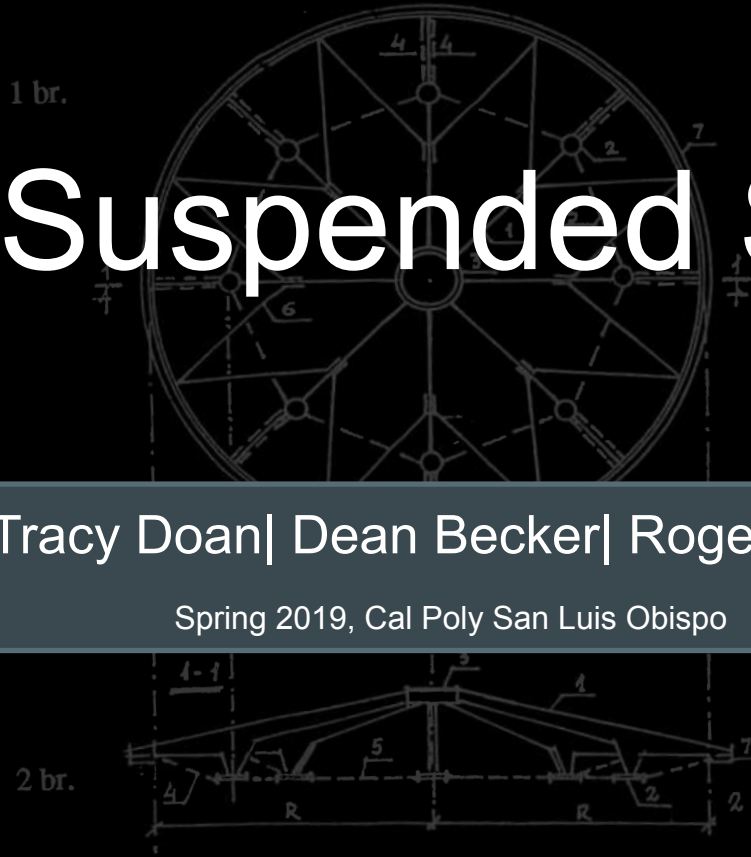# Cable Suspended Structure

Tracy Doan| Dean Becker| Roger Peña

Spring 2019, Cal Poly San Luis Obispo

Biography

Roger Peña

- ❖ **Age: 22**
- ❖ **Raised in Earlimart, CA**
- ❖ **Fourth Year Architectural Engineering Major**
- ❖ **Future employment with Brooks Ransom Associates**
- ❖ **Grew up on a ranch with plenty of livestock including: cows, horses, goats, chickens, turkeys**

Biography

Tracy Doan

- **Age: 21**
- **Raised in Riverside, CA**
- **Fourth Year Architectural Engineering Major**
- **Future Cal Poly Grad Student, MHP intern summer 2019**
- **Grew up in Vietnam**

Biography

Dean Becker

- ❖ **Age: 22**
- ❖ **Raised in Auburn, Ca**
- ❖ **Fourth Year Architectural Engineering Major**
- ❖ **Future employment with KNA Structural Engineers**

Table of Contents

Antanas Panavas

This project was brought to life by the model directly to the right that our senior advisor Ed Saliklis found while in Lithuania. After some searching, he discovered that it was designed by a man named Antanas Panavas (shown in photo in the center). Antanas Panavas was a student of architecture before WWII. During the war, he was imprisoned in a gulag in Siberia with nothing but a book by Nervi called Structures. While in prison, he began the design of his cabled-roof system as shown in the patent on the right. His structure was finally patented in the 80's, yet it was never engineered nor built. The picture in the center is Antanas looking at his patent in the hospital where Ed visited him. Sadly, Antanas has passed away, so this project is dedicated to Antanas Panavas.

Project Goal

- Analyze Antanas' structure
- Learn to model cables with SAP2000
- This is a Geometric Non-Linear analysis due to the large deformations of the structure and not a materials nonlinearity such as we have done in past classes. The stiffness matrix is dependent on the changing shape of the structure due to the fact the cables can experience high deflections.
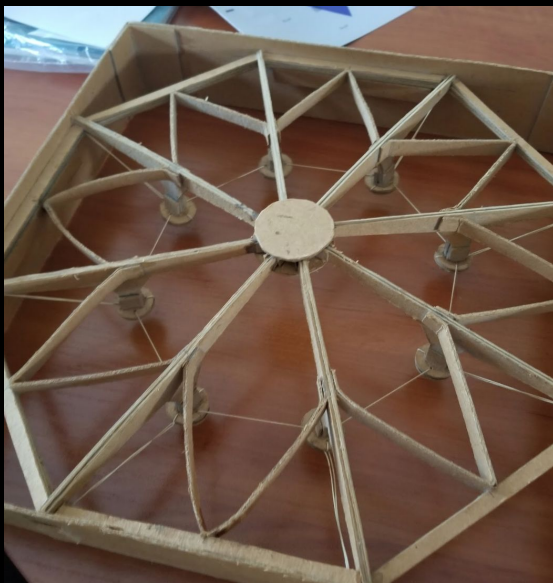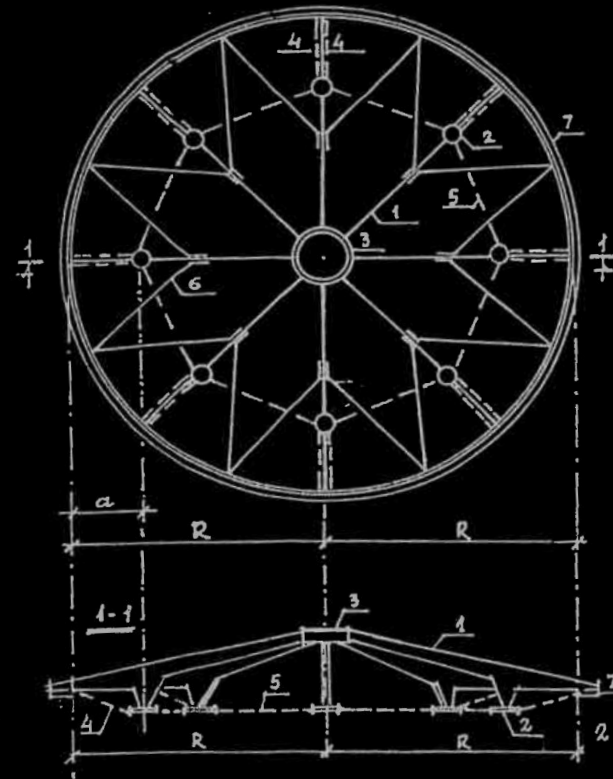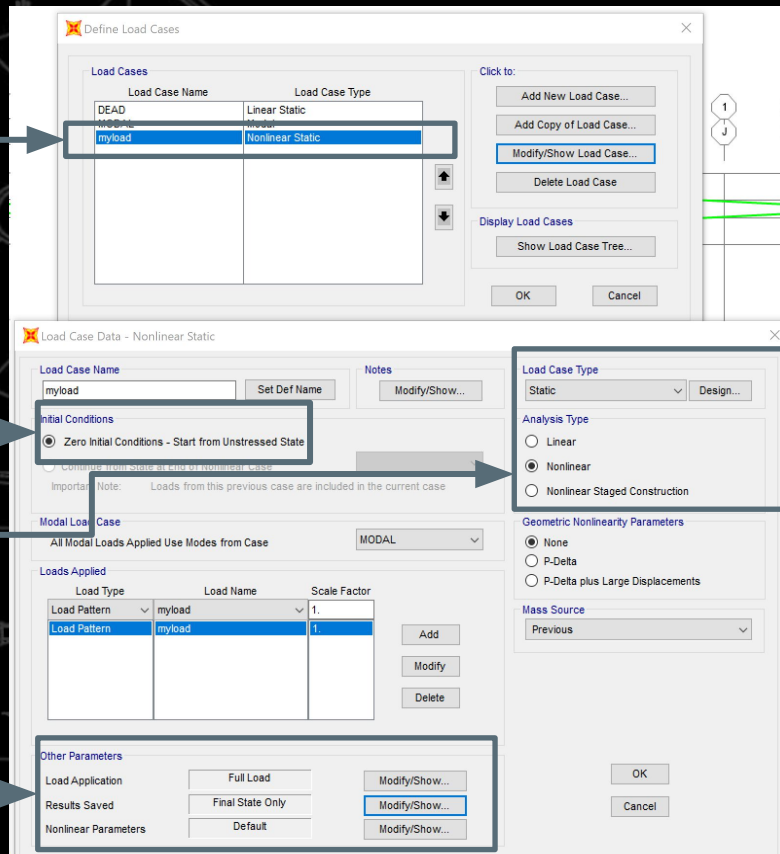
Modeling Cables

Define Load Patterns

- Define your own load pattern with self weight multiplier of 1.0

Define Load Cases

- Modify load case created
- Start from initial condition: ensures no history of saved linear deformations
- Analysis Type: Nonlinear
- Result saved final state only

Modeling Cables

3 Define Section Properties

- Add new section
- + Material Property
- Use steel cable
- Specify steel type: 270 ksi typical for cable
- Specify cable diameter: within 1" for reasonable deflections

4 Set Load Cases To Run

- Only run load case from step 1

Taut Cables

Concept of Taut

- ☐ To model cables in SAP, the first trial of this analysis included using straight frame members (or cables drawn as straight members). But a more realistic method of modeling cables is using the idea of a "taut" cable. Imagine a long, heavy rope; when it's pulled from both sides it become "taut", yet it still has a small amount a sag in the middle. SAP has a very specific definition of what a taut cable is, but to understand some definitions need to be known:
    - ○ Chord length: joint to joint straight distance (or a straight line)
    - ○ Undeformed length: SAP calculates this based on a geometric algorithm: it takes the prestressing tension load that we input and the self weight of the cable and calculates the sag which then gives us a length
    - ○ Deformed Length: The Undeformed length plus strain deformations. For example engineering strain (where strain = $\Delta L/L$ = $(P/A)/E$) or temperature strain.
- ☐ SAP considers a cable as "taut" when the undeformed length is less than/equal to the chord length
    - ○ In other words, before strain deformations are accounted for, the cable should not have any sag.

- ☐ This idea of a "taut" cable is simply the standard SAP uses for modeling "straight" cables and is not overly important. Some firms use specific deflection criteria similar to that found in chapter 16 of the IBC.
    - ○ Any of these methods or criteria is acceptable as long as the cables are <u>not</u> actually modeled as straight members; realistically the cables will have at least a small amount of sag, and this sag will affect the final axial loads and deflections.
    - ○ For this project SAP's standard of a "taut" cable was used.

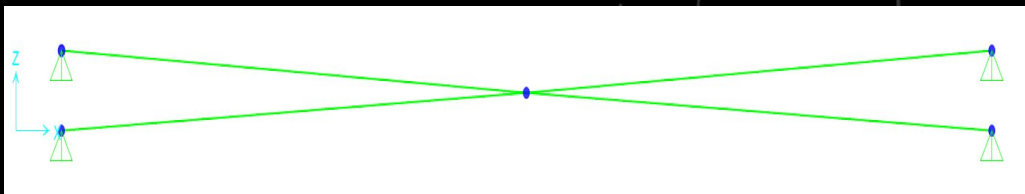# Modeling Cable: 2 Dimensional Structure

Drawing Cables

Method 1: Tension Cable At I or J End

- Input a pretension force and SAP auto-calculates geometry and sag of cable
- Cables need to be taut: stretched tight
- Must change loading under cable parameters until taut which is when undeformed relative length is less than or equal to 1.0

Modeling Cable: 2 Dimensional Structure

Concept: Tension Cable At I or J End

- Cables are not realistically straight, they have some vertical sag
- SAP uses the ratio of the cable's actual length (with sag) over the perfectly straight length to define whether a cable is "taut"
- The load input is the cable's initial prestressing force
- SAP auto-generates the axial & deflections of the cable while taking cable's tautness into consideration
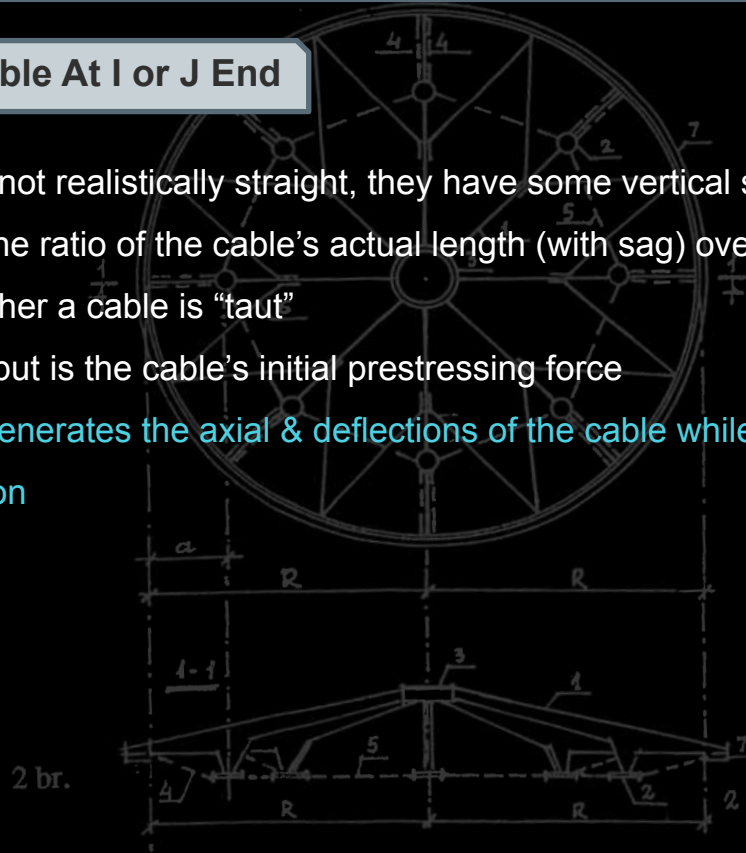
Modeling Cable: 2 Dimensional Structure

5 Drawing Cables

Method 2: Maximum Vertical Sag

- Specify max vertical sag of cable
- SAP will then auto-calculate necessary force on cable to achieve that sag
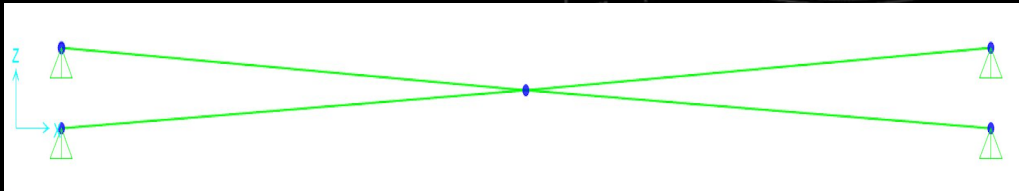
Cable Geometry

File   Edit

Line Object Parameters

Line Object Type	Cable	
Cable Type	Cable - Maximum Vertical Sag	
Section Property	CAB1	

	X	Y	Z
Start	120.	0.	-720.
End	1350.	0.	-780.

☐ Model Cable Using Straight Frame Objects

Line Object Meshing

- ⦿ Keep as Single Object
- ○ Break into Multiple Equal Length Objects
- ○ Break into Multiple Objects with Equal Projected Length on Chord

Coordinate System
GLOBAL

Units
Kip, in, F

Cable Parameters

Number of Cable Segments	1
Added Weight Per Unit Length	0.
Projected Uniform Gravity Load	0.
Tension At I-End	53.6628
Tension At J-End	53.6458
Horizontal Tension Component	53.5903

Refresh

	Deformed	Undeformed
Maximum Vertical Sag	1.	1.367E-13
Low-Point Vertical Sag	0.	
Length	1231.4647	1229.1905
Relative Length	1.	0.9982

Computed Point Coordinates for Linear Segments (Undeformed Cable Geometry)

⦿ Use Undeformed Geometry for Cable Object   ○ Use Deformed Geometry for Cable Object

| Pt.	X	Y	Z	Sag	Distance	Rel. Dist.
0	120.	0.	-720.	0.	0.	0.
1	196.875	0.	-723.75	0.	76.9664	0.0625
2	273.75	0.	-727.5	0.	153.9328	0.125
3	350.625	0.	-731.25	0.	230.8992	0.1875
4	427.5	0.	-735.	0.	307.8656	0.25
5	504.375	0.	-738.75	0.	384.832	0.3125
6	581.25	0.	-742.5	0.	461.7985	0.375
7	658.125	0.	-746.25	0.	538.7649	0.4375
8	735.	0.	-750.	0.	615.7313	0.5

Planar View

OK   Cancel

Modeling Cable: 2 Dimensional Structure

Concept: Maximum Vertical Sag

- Identical to method 1
- Manually input a desired vertical sag for architectural purposes
- SAP auto-generate the pre-tension force of the cable required to achieve that sag
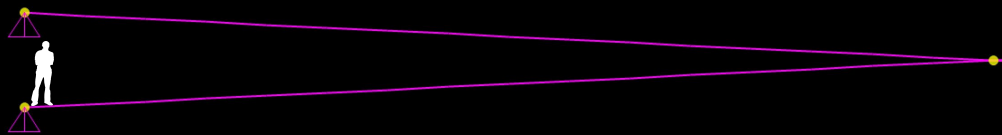
Straight Frame Object
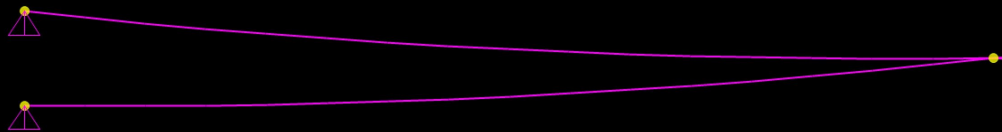
Max Vertical Sag

Structural Concept: Catenary Action

- As stated previously these methods that use "taut" cables and include sag are the most realistic representation of a cable, the main reason for this is catenary action.
- The main idea of catenary action is that the larger the initial sag, the smaller the axial load from external loads will be.
  - It's important to note that to create a cable with a larger initial sag, the user must input a lower prestressing force. This lower force accounts for some of the decrease in final axial loads shown in yellow below.
  - However the shape of the cable also plays a part in decreasing axial loads; the greater the sag, the smaller the axial force (this can be proved by performing a statics check of a point at one of the supports)

NOTE: The purple lines are the cables' initial sag (before any deformations from external loads), the axial loads shown in the boxes on the right are the final axial loads (in yellow) minus the prestressing force put into the cable. This is meant to show how the axial loads decrease with respect to the shape of the cable
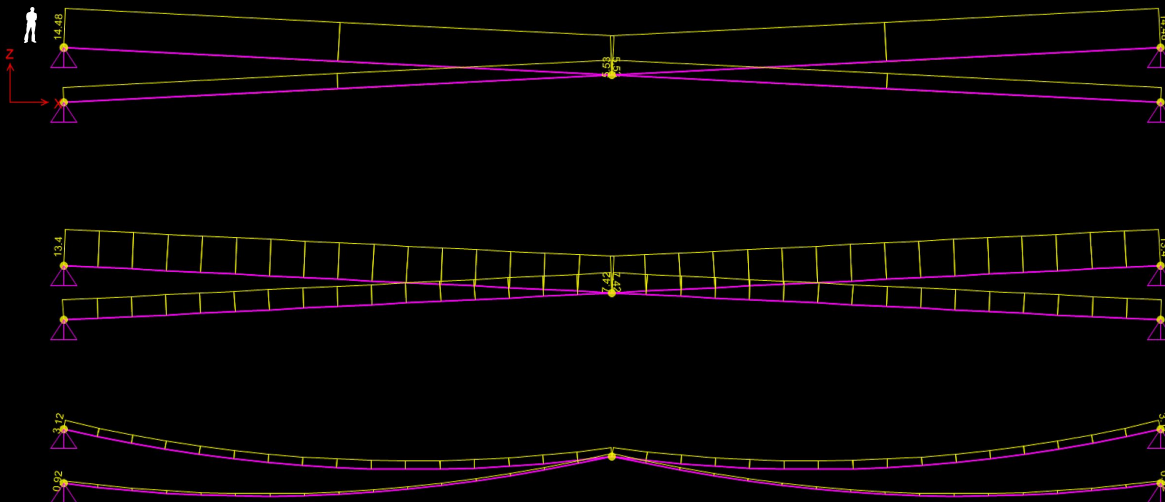
1 Sag: 0"
Prestressing force: 10 k

Top Axial = 4.48 k
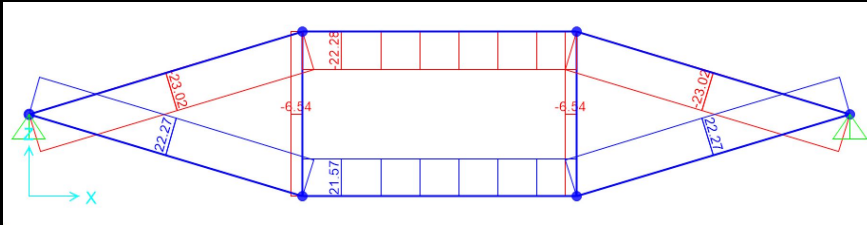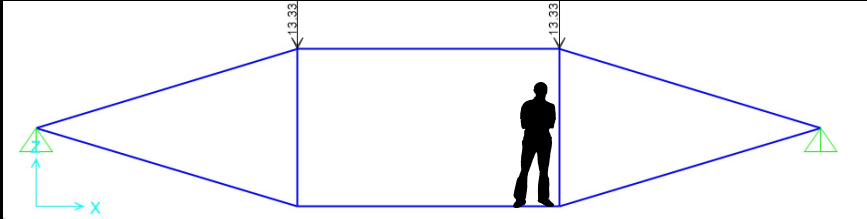Bottom Axial = 4.47 k

2 Sag: 5"
Prestressing force: 10 k

Top Axial = 3.4 k
Bottom Axial = 2.58 k

3 Sag: 55"
Prestressing force: 1 k

Top Axial = 2.12 k
Bottom Axial = 0.08 k

Cable Truss Model

A 2D Truss Model
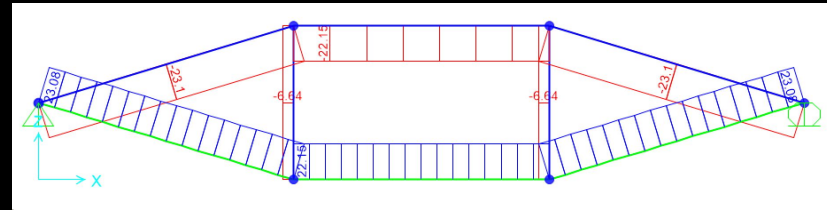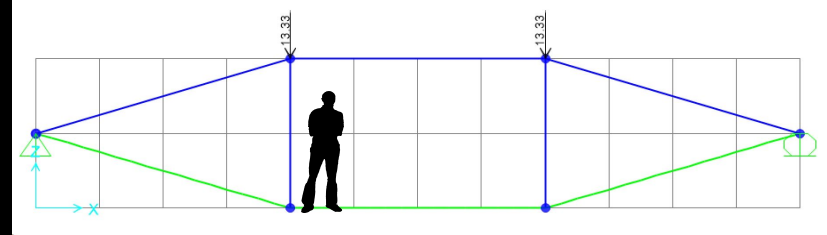
B 2D Half Cable Truss Model

Analysis

Analysis

❖ Initial analysis consisted of a truss spanning 40 ft (height = 8 ft) and two point loads of 13.33 kips with regular straight frame members to acquire a sense of axial loads that should be expected when analyzing a cable truss and to also get an idea of what pretensioned load should be inputted.

NOTE: Blue lines indicate regular straight frame elements; Green lines indicate cable elements

❖ The next set of analysis involved the same truss but with cables modeled as tension at I-end for the bottom elements of the structure. Pretensioned load was set to 23 kips and we observed about 23 kips of both tension and compression on bottom and top members very similar to the regular truss with straight frame elements analysis.

Cable Truss Model

## C — 2D Full Cable Truss Model
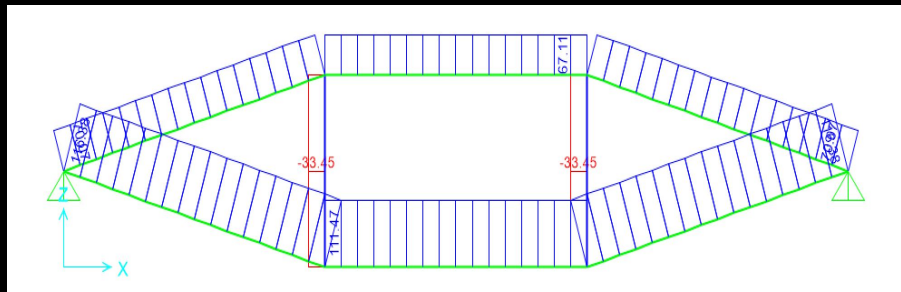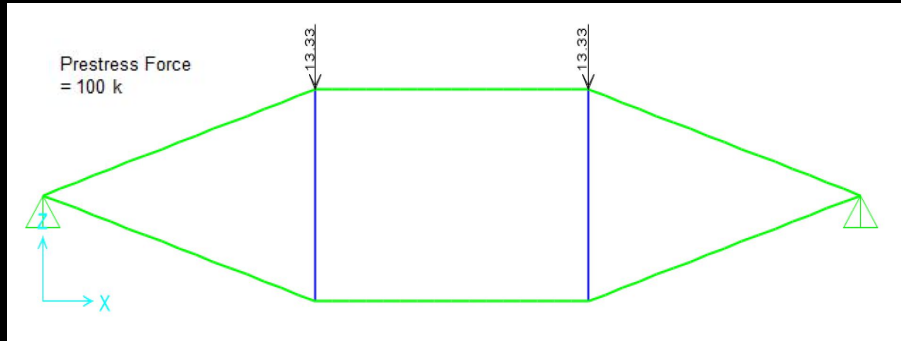
NOTE: Blue lines indicate regular straight frame elements; Green lines indicate cable elements

Analysis

➢ In order to verify the modeling process for cables is correct, the same truss was analyzed with cables as the top and bottom elements and only the struts were able to take any compressive load. Cables cannot take any compressive strength so if the modeling process is correct, there should be tension in all cables if a sufficient pretensioned force is applied. For this case, a pretensioned load of 100 kips was applied and it was observed the top cables experience a final tensile force of 67 kips and the bottom members experience a final tensile force of about 111 kips. This helped verify the modeling process was correct; the top cables are losing tensile force due to the fact that they would originally experience compression while the bottom cables are gaining tensile force. It is interesting to note that the change in tensile force between the top and bottom members is non-linear, there was a 11% increase in tensile force on the bottom members while about 33% decrease for the top cables. The top members are losing tensile force faster than the bottom members are losing tensile force because this is a non-linear analysis.

3D Modeling: Antanas' Structure
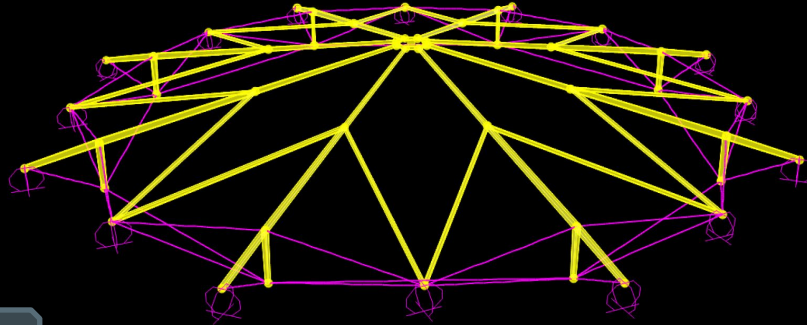

Self-stressed System:

Antanas' structure is self-stressed system, this means that it is a tension-compression system that is internally in equilibrium. A good example of this is a kite. In a kite there is wood in compression, and string and paper that is in tension. The kite is internally stable, but it is still able to move around freely. This type of system has many benefits including constructability and efficiency. A good example of a self-stressed system in the real world, is Kawaguchi's Pantadome System.

Efficiency:

Antanas' structure is extremely efficient for two main reasons; the tension ring (shown in purple above) and the geometry
- ➢ The tension ring pulls the roller supports inward, resulting in uplift at the center. (A self induced camber)
- ➢ The geometry causes the structure to be very stiff. This is true even when using wooden members with a very conservative modulus of elasticity of 850 ksi and reasonable member sizes no greater than 8-¾" x 24" glulams (Area = 210 in^2)

3D Modeling: Antanas' Structure
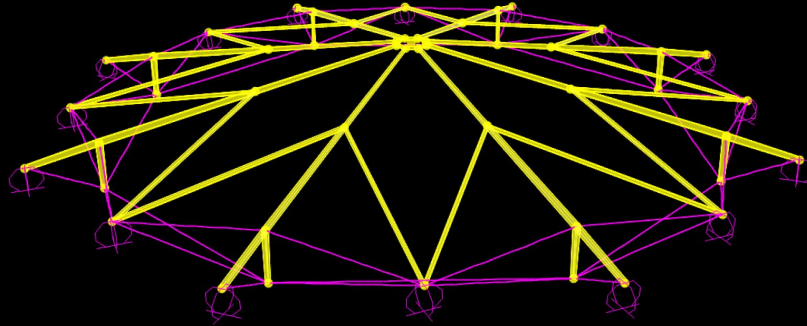
Efficiency (cont.):

This roof structure is meant to span large spaces such as stadiums. In this model, dimensions and loads are as follows:

- ➢ Clear span: 200 ft
- ➢ Maximum clear height: 30 ft
- ➢ Strut height: 14 ft
- ➢ Angles between ribs: 45°
- ➢ Point Load at center: 88^k (this is could be a scoreboard load for example)
- ➢ Uniform Load along each rib member: 10^{PLF} (a cladding load)
- ➢ Self Weight of all members including cables

Even with these large spans, reasonably sized members, and fairly conservative loads, this structure only deflected about 1.2"

3D Modeling: Antanas' Structure

Non-prismatic Member Design

1 Define Material Property

2 Define Section Property

Specify:
Member dimension

3 Define Non-prismatic Section

Specify:
Member start section
Member end section

Specify:
Weight per unit volume: 35^{PCF} typical
Modulus of elasticity: per species of wood
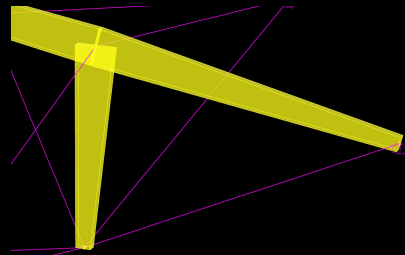
	TAPERED BEAMS
LOADING:	
Point Load at Center	11 kips per joint
Distributed Load	10 lbs/ft each frame
Self Weight	35 pcf * area of member
Cable Prestressing	62 kips
MATERIAL PROPERTIES:	
Cable Material	A416Gr270
Modulus of Elasticity (timber)	850,000 psi
SECTION PROPERTIES:	
Cable Diameter	1 inch
Inner-Radial	8-3/4" x 18"-12"
Outer-Radial	8-3/4" x 24"-18"
Col+Outer	8-3/4" x 24"-12"
Blocking	8-3/4" x 12"
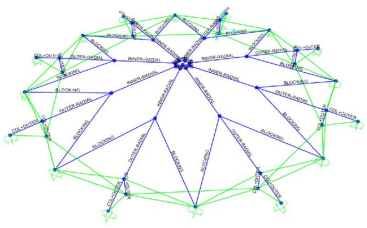
3D Modeling: Antanas' Structure

Sizing Member

$Sxx = Moment/Fb$

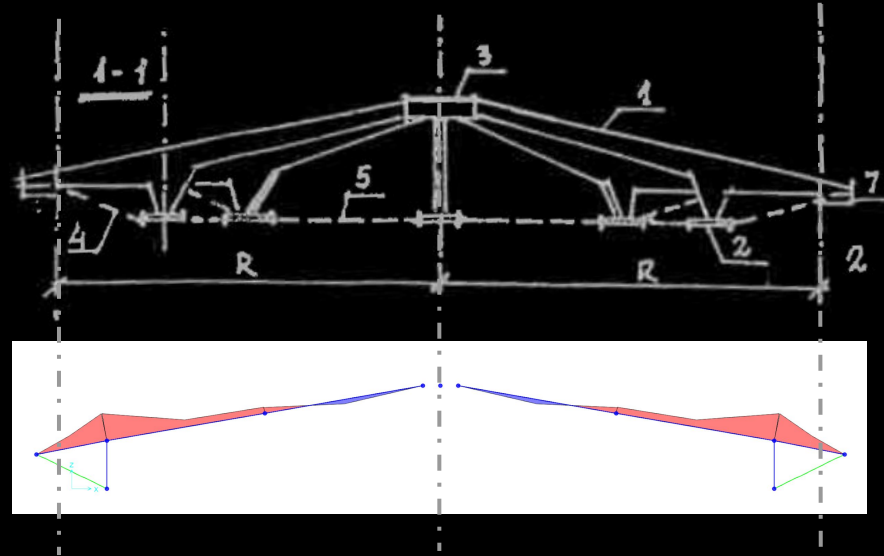Sxx = Section Modulus

Fb = Bending Stress (psi)

Moment demand from SAP

Non-Prismatic Beam Design

Tapered beams allow members to be smaller overall and only large where the moment demand is largest.

Deflections

Tapered Beams are more efficient.

It is interesting to see the moment diagram under gravity loads only is very similar to the shape of Antanas' structure in section view seen above.

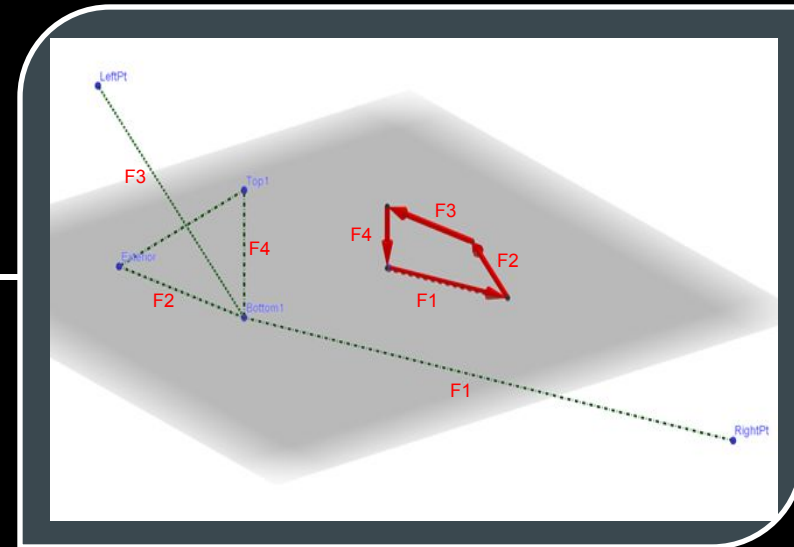# Equilibrium Check: Graphic Statics

Graphic Statics Using Geogebra

1 Model vectors magnitude in direction of component joining end to end

2 Connect final vector as composite magnitude of all vectors (square root of sum of all vector component squared)

$$F4 = \sqrt{F1^2 + F2^3 + F3^2}$$

3 In equilibrium when final vector closed with first vector
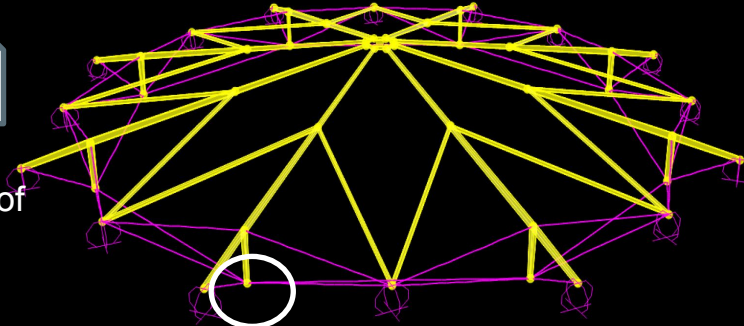
3D Model Results
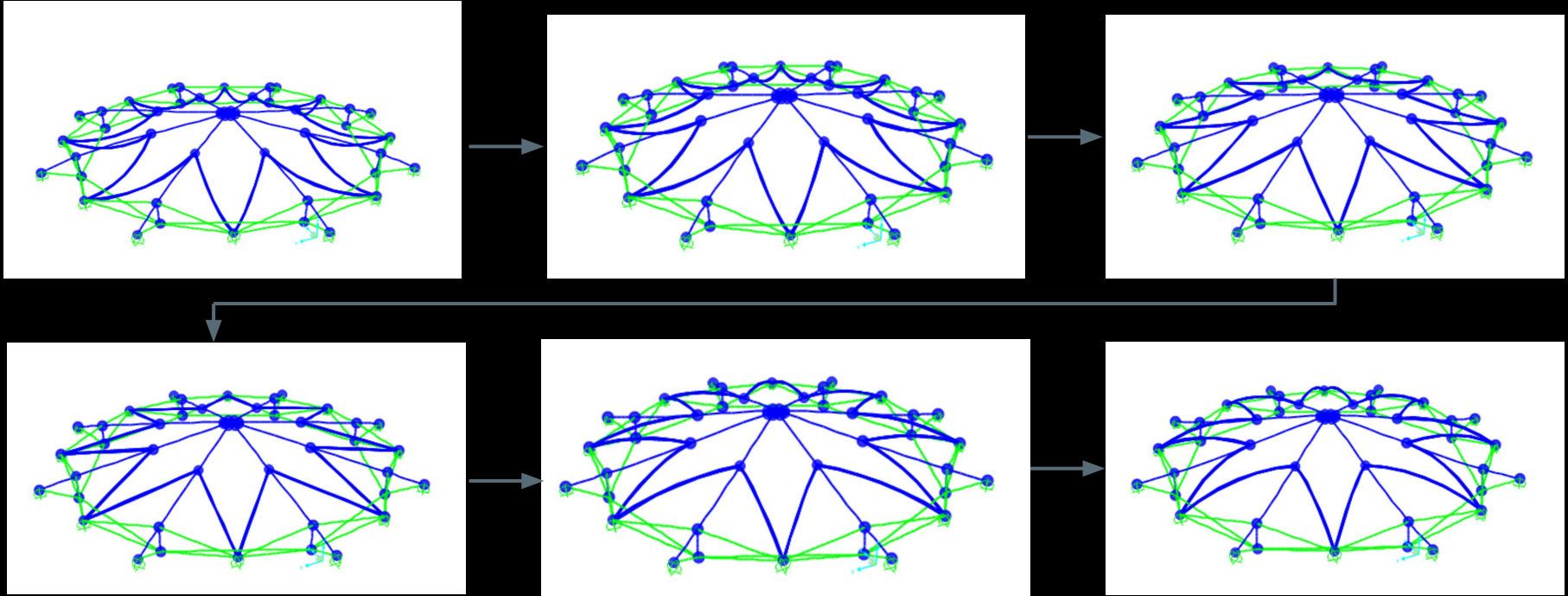
❖ This is the deflected shape of the structure throughout the loading process. The initial photo is the result of the prestressed forces in the cables causing the structure to pull towards the center and cause uplift and then the external loads cause the structure to deflect downwards to about 1.2"

One of the most important parts of this structure is the prestressing load in the cable ring. The stiffness of the structure - and therefore the deflections - depend on this prestressing load. However it is important to note that unlike the 2D model explained on pages 11-12, the final tensile force found in this cables is unaffected by this prestressing load.

- The prestressing load is determined by an iterative process based on allowable deflection at the center.
    - The user should first replace each cable with a straight frame member and run the model in order to find a reasonable starting point for a prestressing load.
    - In this model a final tensile force of 33.9 kips was found for the frame model. Therefore, a 32 kip prestressing load was used for the first iteration.
- The boundary conditions of this structure are different than those in the 2D truss, this is the reason the final tensile force found in this cables is unaffected by this prestressing load. In order to analyze this structure:
    - SAP first brings the structure to equilibrium by taking the prestressed load and distributing it throughout the system in the form of deflections.
    - At this point in the analysis, the tension in the cables is about zero, and there are major deflections throughout the structure:
        - There is uplift at the center, and the roller supports have been sucked in toward the middle of the structure.
    - SAP then takes this deformed structure, and analyzes it with the applied loads (the point load, the distributed loads, the self weight)
    - These loads put tension back into the cables (for this model and loading, the tension came to about 30 kips)
    - This final tensile force is based primarily on the:
        - Applied loads (which never change)
        - The geometry of the structure (which changes only slightly from the deflections)
- Therefore no matter what the prestressed load is, the final axial loads will be the same. The changes only occur in the deflection and stiffness of the structure
- In summary, the larger the prestressing load, the smaller the deflections and the stiffer the structure, but the final tensile force will be unaffected.

	FINAL TENSILE FORCE	DEFLECTION
FRAME	33.9 Kips	7.7 inches
32 KIP PRESTRESSING FORCE	29.7 Kips	9.6 inches
62 KIP PRESTRESSING FORCE	29.2 Kips	1.2 inches
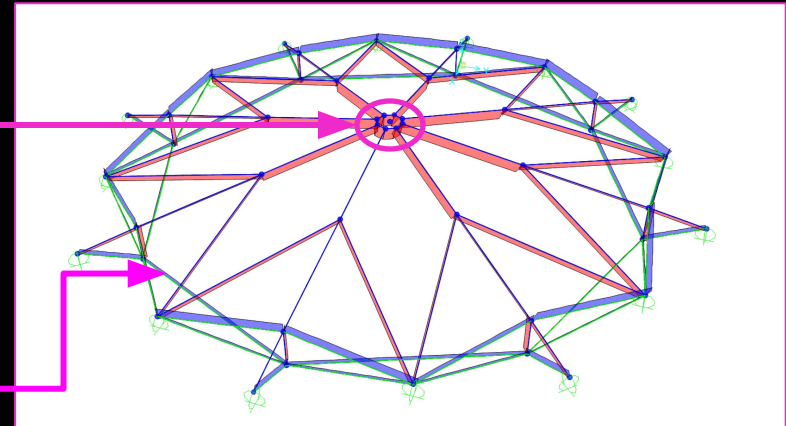
Other Project Considerations

At the time this structure was being designed, the Soviet Union was pushing for increased construction efficiency and significant reductions in building weights. They needed large covered spaces quickly and at a lower cost. We believe that while the world is no longer in a time of war, these types of buildings are still needed. In addition, the type of structure that Antanas has designed is more than a simple covering such as a warehouse. It is also architecturally pleasing, yet maintains the structural standards required today. His structure uses cables and tapered timber beams which results in less materials and a much smaller carbon footprint. Furthermore, it is a self-stressed system which means it can be prefabricated in pieces and built on the ground on site, and then lifted into place. This saves tremendously on labor costs and safety concerns during construction. All in all Antanas' structure is a very efficient and economical roof system that will add value to any community in which it is built.
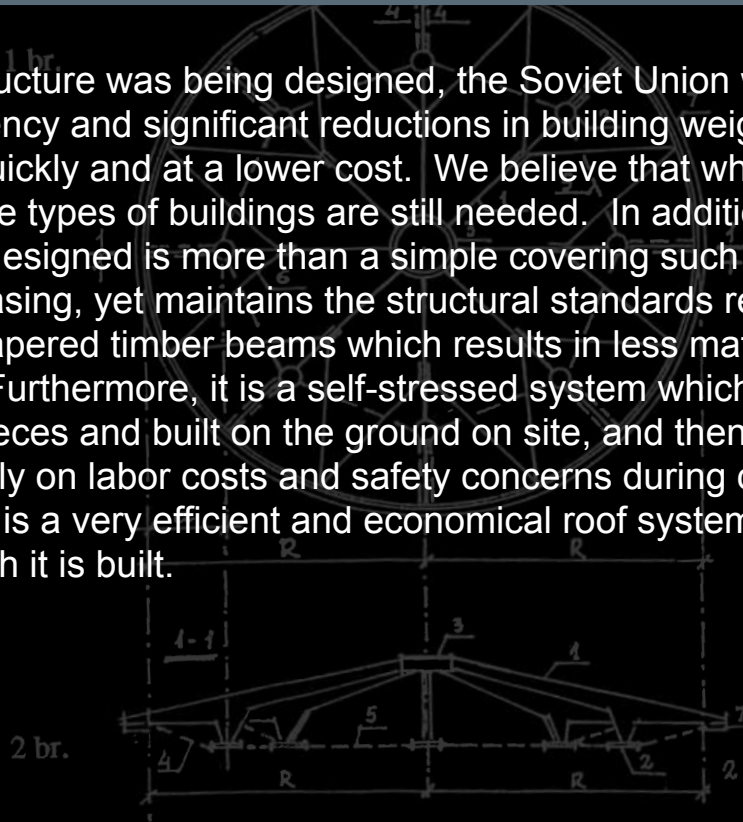
Reflections

Learning on our own

➢ We had to learn how to model cables and how to use SAP2000 on our own. Many techniques were used in learning this program and analysis. We used our advisor's knowledge, saw many tutorial videos, and did research online. We also had professionals help and discuss our process and verify our analysis.

Overall

➢ We had a great experience working on this project. From the beginning of the journey with Antanas' inspiring story to our final analyzed model, we were able to learn many different modeling techniques and concepts we would not originally learn in the undergraduate curriculum here at Cal Poly. We were able to dive into the world of cables and geometric nonlinear analysis and expand our knowledge while trying to continue this man's dream. Although he has passed away, all this research and analysis is still dedicated to Antanas Panavas and this work will be brought to any surviving family members to honor Antanas. We hope our work and research can be expanded on and continued by future students in the following years. We hope that one day this structure may be built in the real world.