Dulles International Airport, Virginia.

Eero Saarinen

"Almost two miles away across the green Virginia countryside the great building comes into view with its classic lucidity, massed in white splendor on its monumental base, its giant columns rising like muscular arms to hold aloft the long brow of the roof, and one knows immediately that this is the fulfillment of the search."[1]

Structural Descripton/Aspects

- The piers lean outward which attempts to offset the tension forces acting inward.

- This created compression at the base of the piers with an angled resultant that passes through the angled pier to the base.

- The load on the concrete slab at the base of the system would be from all the piers transferring compression to it due to the tension forces pulling them inward.

Live Loads:

- For live loads, the building deals with snow on a roof with a caternary form. Lateral forces from winds could have a small effect. Temperature change would also effect the expansion and contraction of the concrete components of the system.

Dead Loads:

- Roof consists of steel suspension cables spanning between the concrete piers which are given stability by concrete elements laid on top of the cables.

- The lower ground level is simply slab on grade, with no supports running vertically to the roof it acts as a compression piece between the two concrete piers holding them apart from the inward acting forces at the base due to the nature of the system.

- Standing in the center of the roof, the load would be transferred in tension to the ends of the cablis supported by the piers.

- Then it would transfer downward to the ground through the massive reinforced concrete objects, finally kept in equilibrium due to the slab between the piers keeping them from pulling inward.

- The structure of the roof, piers, and floor act as a complete system, allowing all the stuff in between to seemingly float freely, not limited by the structure.

Lateral Loading:

- Lateral loads are taken care of in the transverse section by the contrasting cantilever of the concrete piers and the suspension cables acting in the other direction.

- This provides support in two directions with the dead load of the pillars causing a bending moment in one direction and the tension forces of the cables in the opposite direction

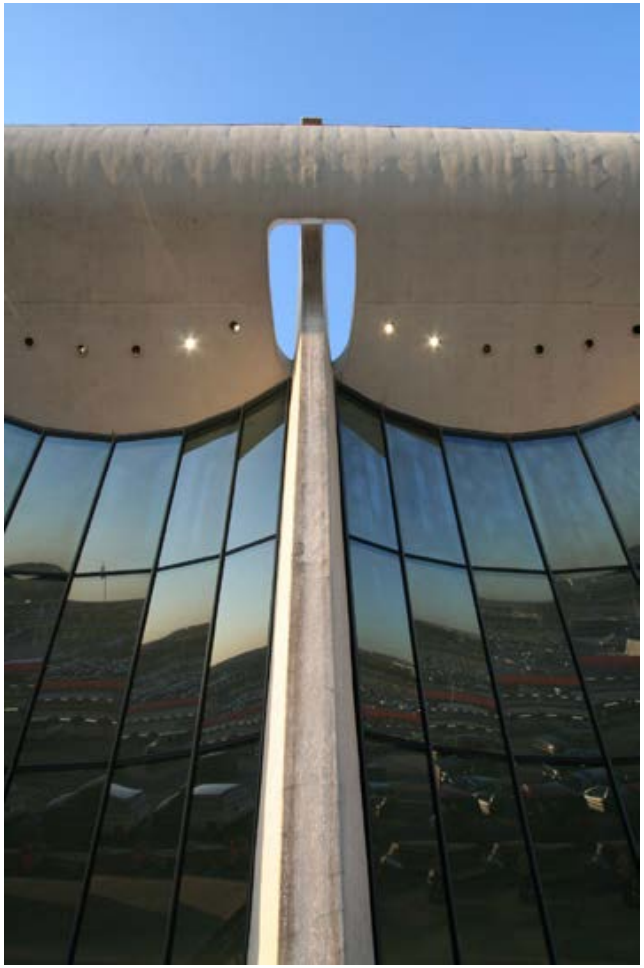
- In the other section longitudinally, the concrete piers are spaced apart by a horizontal concrete beam which runs along the tops of the piers spaced 12 meters apart.

- This beam not only helps resist lateral loads, but also provides a place for the roof to bear in between the piers. With them all anchored deep into the ground, along with a concrete roof structure providing added stability, the lateral loads are compensated for adequately in all four directions.

- Due to its low profile, and the afore mentioned forms of stability, wind loading is not significant in effect upon the stability of the structure.

The concrete piers are also tapered in all four directions, giving them each stability in all four directions from lateral loading. This individual stability contributes to the overall strength of the system. This is perhaps the primary resistance to lateral loads for the entire system. Each pier is independently supported in all four directions giving them each individual stability as in the case of a flagpole. Thus, they do not need much lateral bracing because of their structural independence. The foundations for these piers are also important because they are poured very deep into the ground for added lateral stability, and also are connected to the concrete slab which runs transversely between each pair of piers. This slab provides compression resistance for the whole system while also further stabilizing each individual support.

If you were to load the side of the structure laterally, visually, it would seem like the leaning piers could possibly tilt inward, especially since the cables are already acting in that direction. However, this is highly unlikely since the piers are of extremely high mass buried deep into the ground tapering to a much smaller cross-section towards the top. It would take an extreme force acting laterally to cause the massive foundations to rotate at the bottom.

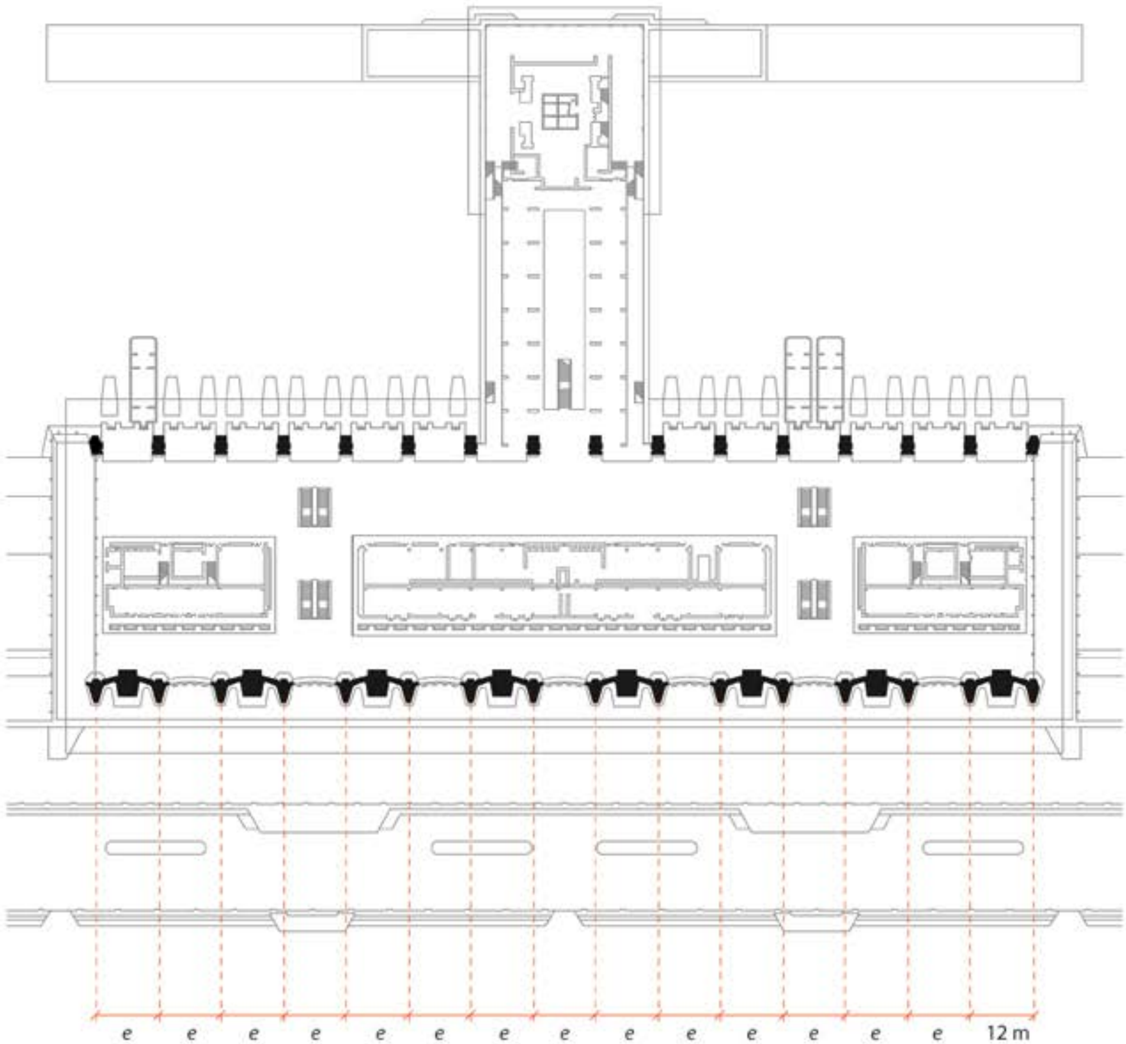


Lateral loading in the longitudinal direction would be more likely to effect the building's stability, except that these two glass walls are structurally independent of the main system. The most that would happen would be the glass collapsing, but having no effect on the roof.
Scale is also a factor in the overall stability of the entire system due to the massive size of the members, and the great spans created by them, it also would take sizeable loads to have a significant effect on the system, loads not present in the form of wind (unless a hurricane rolled through).

When looking at expansion and contraction of the concrete due to temperature change, this is compensated for by the nature of the suspension cables. When there is expansion or contraction, the cater nary shape of the spanning cables will become flatter or deeper to compensate. Also since steel and concrete have similar moduli of elasticity, they tend to expand and contract at the same rate giving the system a continuity of deformation.

Simply Suspended Cable System

Unlike other cable system, since it is not pre-tensioned, this suspended cable roof would fail beyond a certain span as deflection in the non pre-tensioned cable grow exponentially with span. In order to counter this, this type of structural system relies heavily on the material properties, balance and scale as well as understanding the nature of funicular structure of which created a whole co-dependant system to ensure structural equilibrium and overall stability.

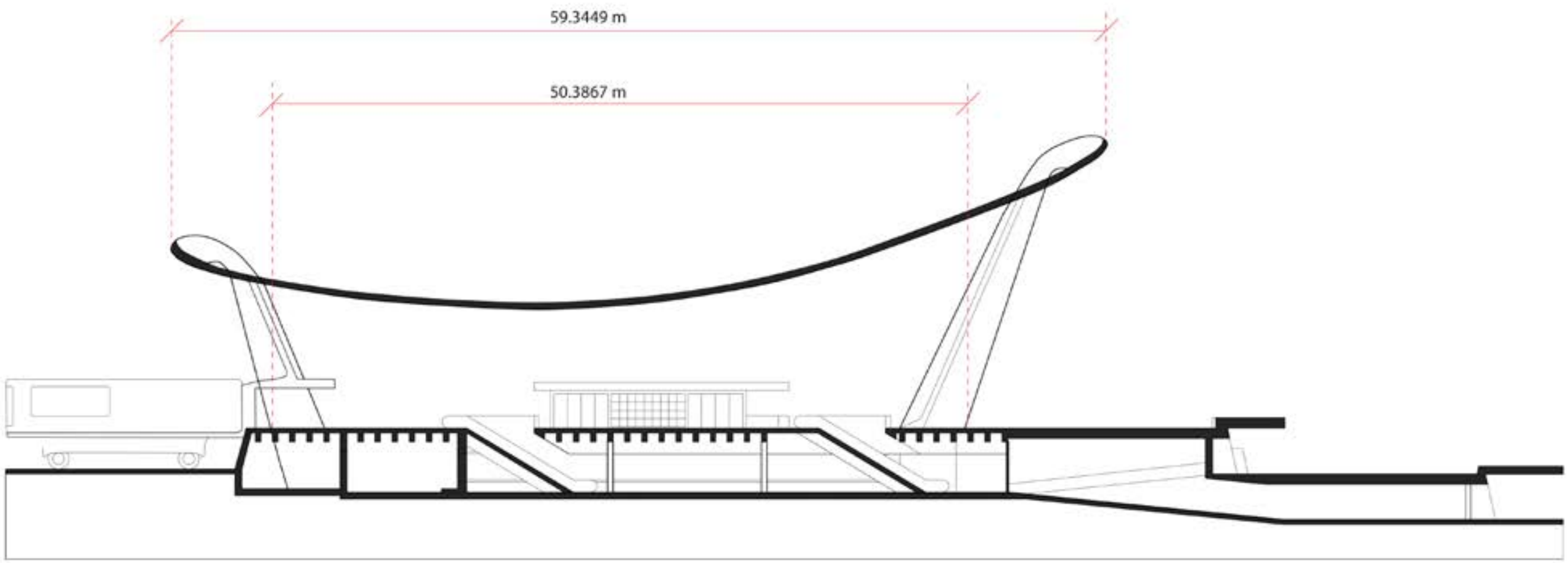


BUILDING PLAN
Scale 1:1000

Building Structure: Section

Simply Suspended Cable System

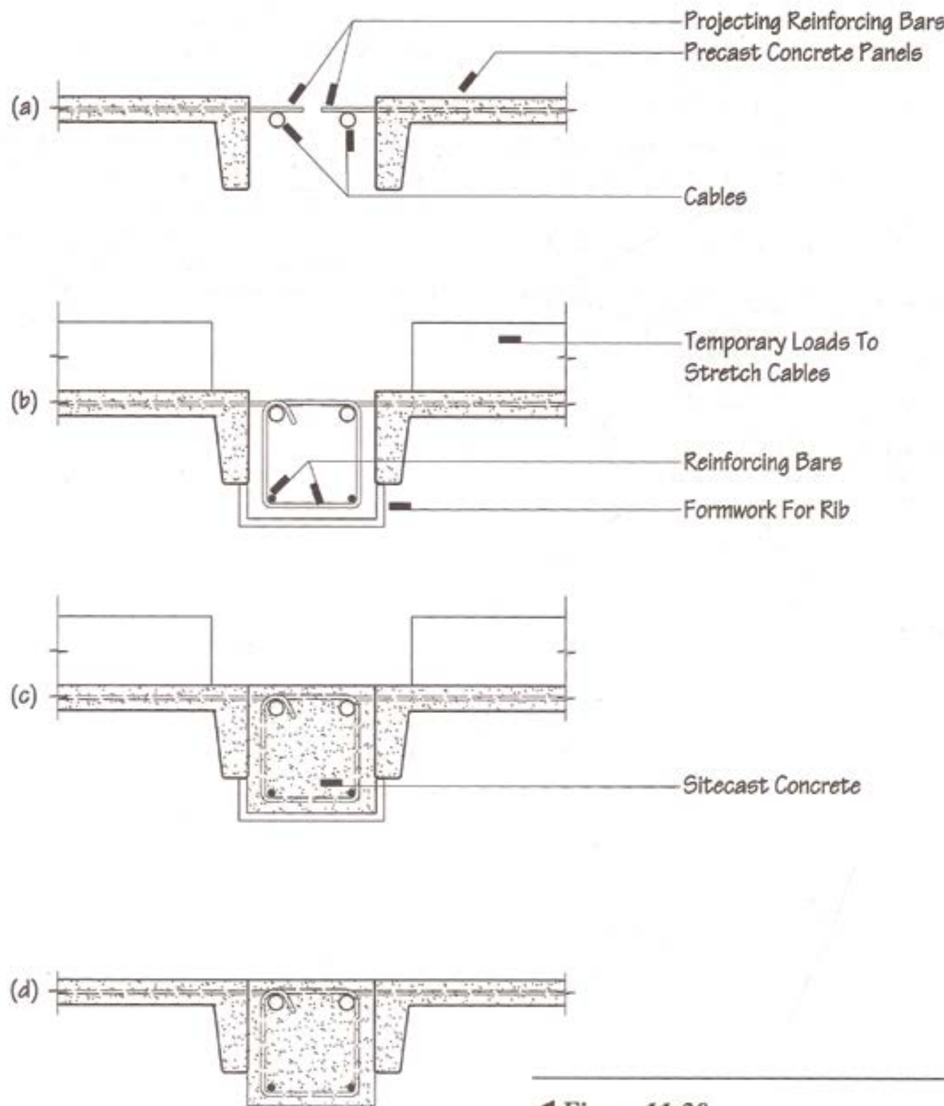
Dulles airport has a wide-span roof structure to allow maximum use of interior space and free of columns to accommodate architectural programme as well as to achieve an elegant quality of space that suggest flight and lightness. Therefore, simply suspended cable system is employed to both shape and support this architectural form with simplest gesture.



BUILDING SECTION
Scale 1:300

Material Properties

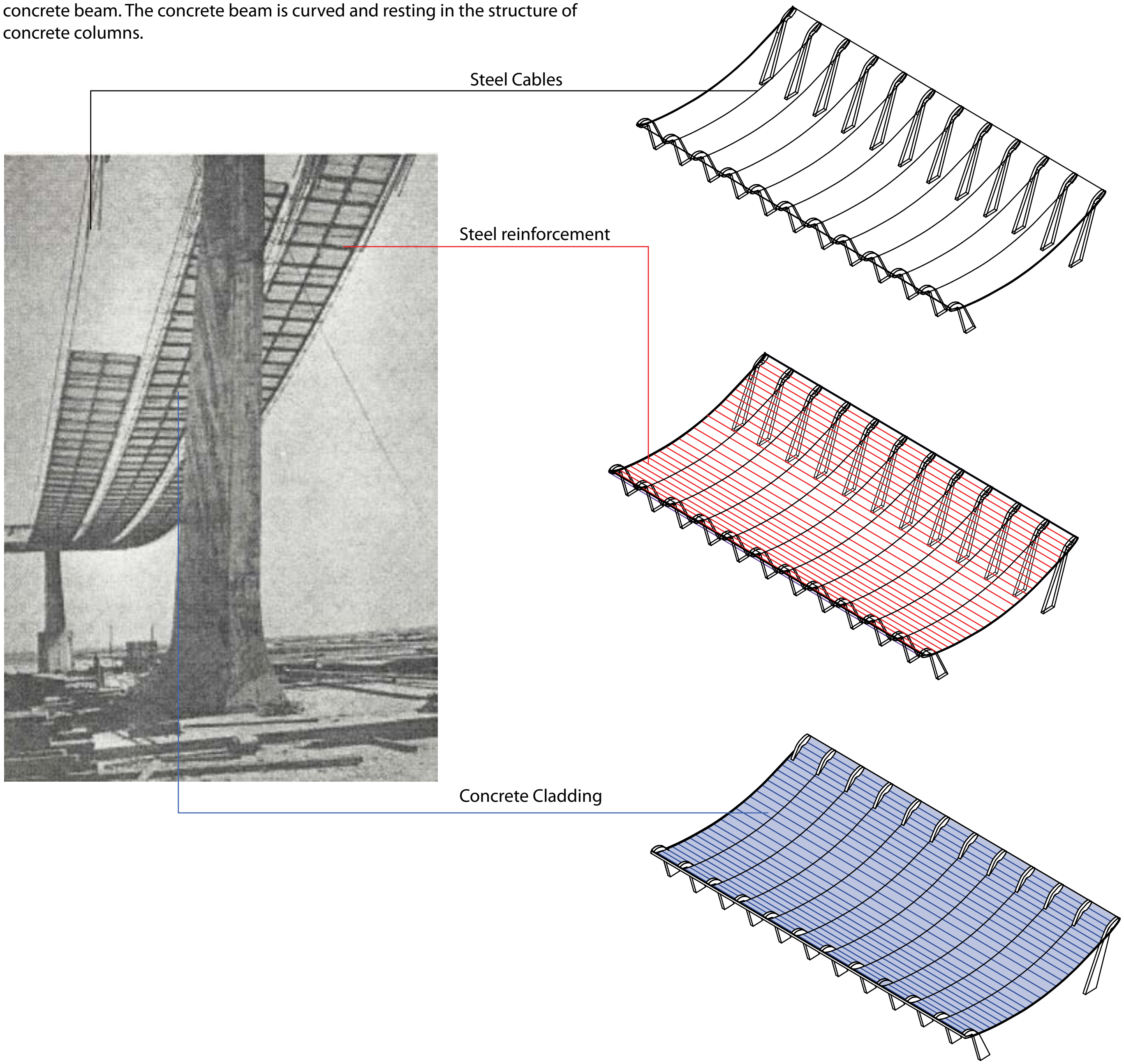
Material Properties:[2]

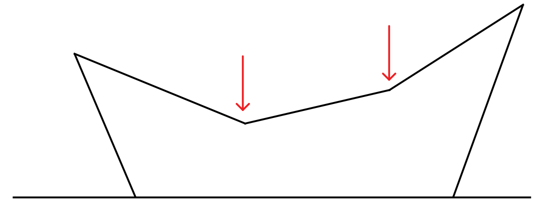


◀ *Figure 11.30*
How the deck was attached to the Dulles roof.

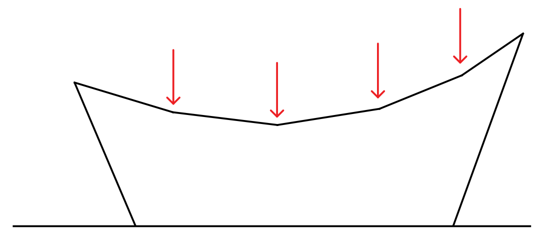
Suspended Cable Roof System as Funicular structure

This suspended cable system is a funicular structure that forms a catenary shape. This catenary shape is characterized by its formation due to the precast concrete slab that follows the curve of the cables that is suspended to the site concrete beam. The concrete beam is curved and resting in the structure of concrete columns.

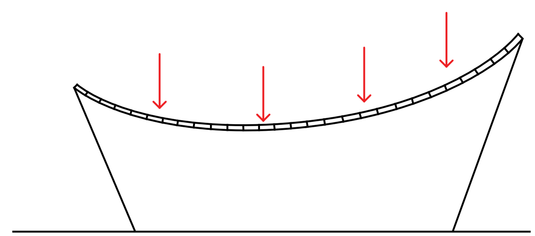




It is found that the cable shaped according to the force that is applied on its body. This is due to the fact that the horizontal component of force is found constant throughout the length of any hanging cable that carries only vertical load and thus the form shaped due to reaction to vertical forces.



In achieving an elegant catenary shape for the Dulles airport, it is predicted that the form of the overall roof structure is attained by distributing load on smaller intervals on the suspended cable. This is achieved by applying steel reinforcement connecting the cables on each bay.



In order to make sure an equal loading, precast concrete cladding is applied on the cable roof to sustain the uniform loading. An optimum amount of thickness of 200mm slab and its rigid property that locks each other gives a self-weight to the whole span of the cable therefore forms a smooth catenary structure.

Calculating Roof Weight

Weight of the Roof: 112.852 KN

Load Per Meter Square: 10.33 KN

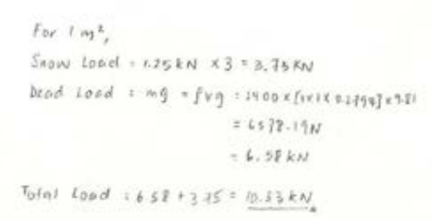
Load on the Model: 76.68 Kg (= 0.75 KN)


Weight of roof = ρV × 9.81
= 2400 [179.85 × 0.2794 × 60.75] × 9.81
= 71,864,610.72N
≈ 71865 kN

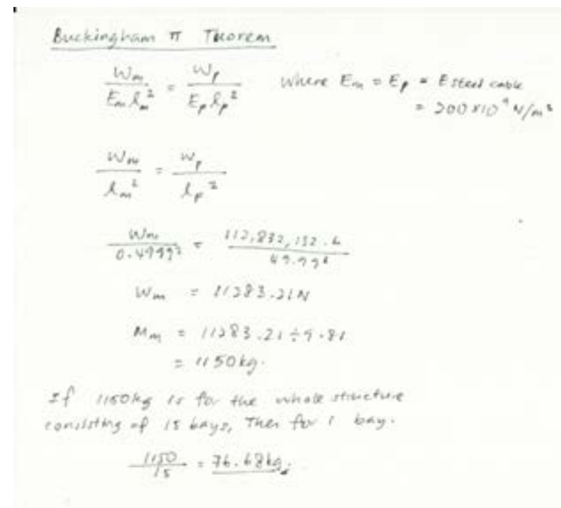
Snow Load = 1250 × (179.83 × 60.75)
= 13,655,890.63N
≈ 13,656 kN

Active Load = Snow Load × Safety factor of 3
= 13,655,890.63 × 3
= 40,967,571.88
≈ 40,968 kN

Total Load on Roof
= 71864610.72 + 40967521.88
= 112,832,132.6
≈ 112,832 kN


For 1 m²,
Snow Load = 1.25 kN × 3 = 3.75 KN
Dead Load = mg = ρVg = 2400 × [1×1× 0.2794] × 9.81
= 6578.19N
= 6.58 kN

Total Load = 6.58 + 3.75 = 10.33 kN


Buckingham π Theorem

$$\frac{W_m}{E_m l_m^2} = \frac{W_p}{E_p l_p^2}$$ where $E_m = E_p = E_{steel\ cable} = 200 \times 10^9\ N/m^2$

$$\frac{W_m}{l_m^2} = \frac{W_p}{l_p^2}$$

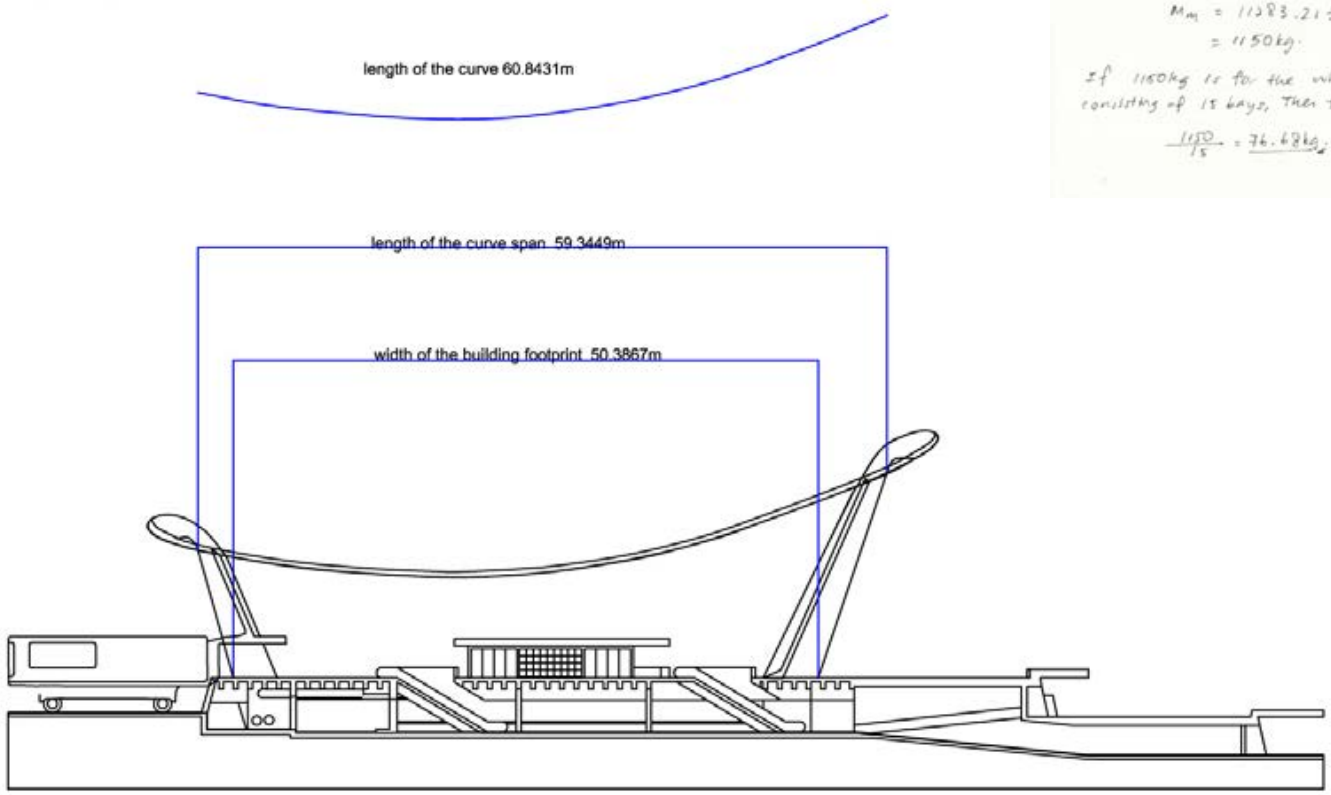
$$\frac{W_m}{0.4999^2} = \frac{112,832,132.6}{49.99^2}$$

$W_m = 11283.21N$

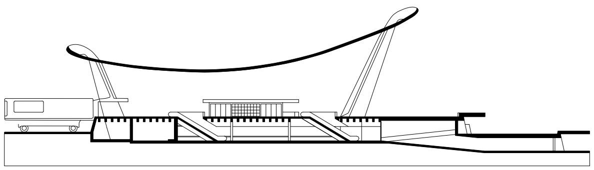
$M_m = 11283.21 \div 9.81$
$= 1150kg.$

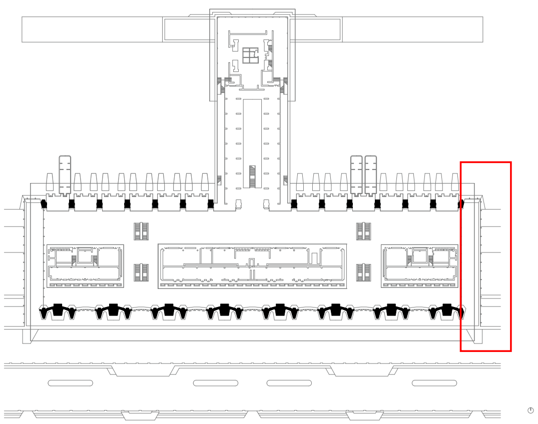
If 1150kg is for the whole structure consisting of 15 bays, Then for 1 bay.

$\frac{1150}{15} = 76.68kg.$



Model Construction

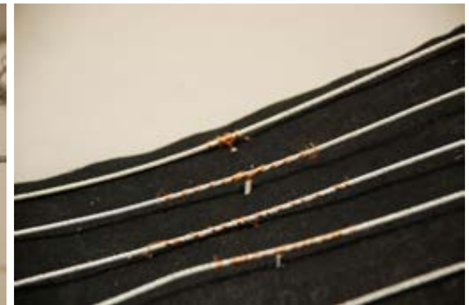


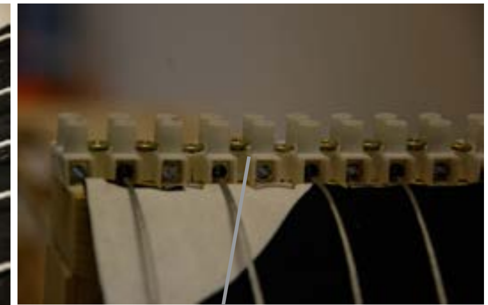


Testing 1 Bay, consisting of four columns.

Model Scaled at 1:100.

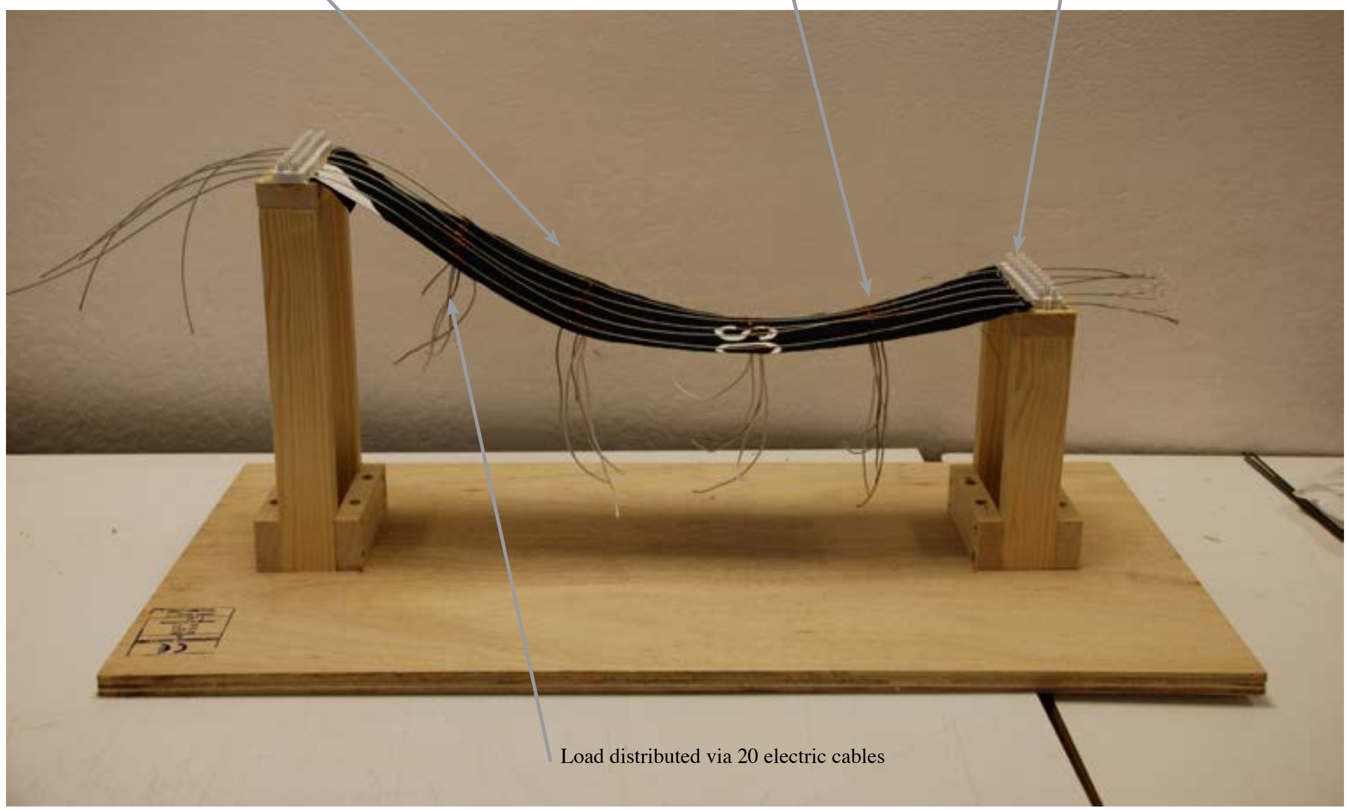
The width of the bay including columns is 12cm by 50cm interior distance. Height has been exaggerated but is in proportion, to give extra space to test model.



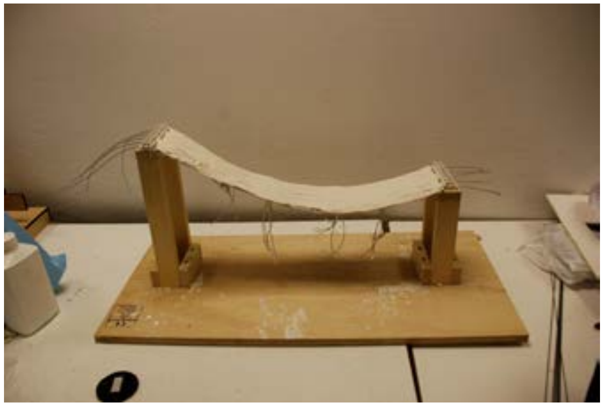


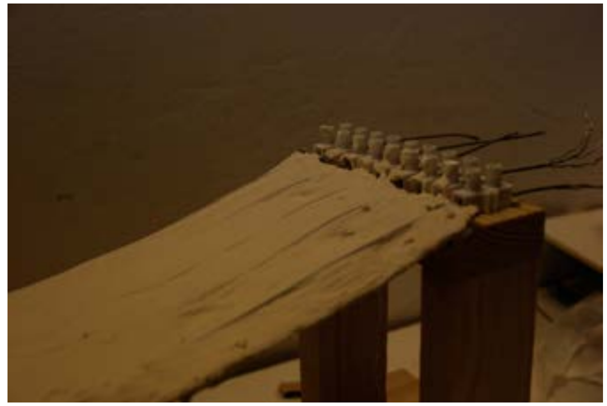
Using cotton cloth to both give natural curvature and spread the wires at the specific distances apart from one another, using electrical wire to hold and distribute main weight from load to roof.

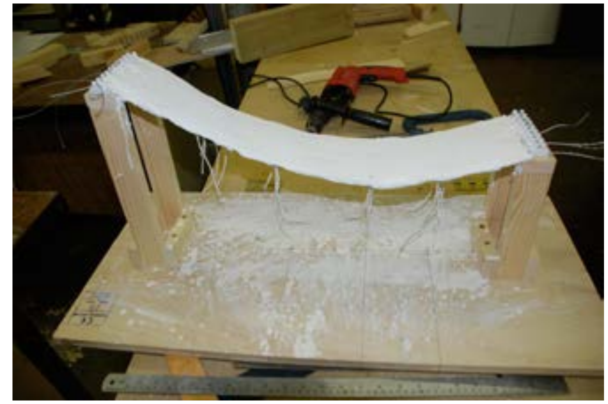
Stapling cloth together with pre-tensioned wire held down using electric wire connections.



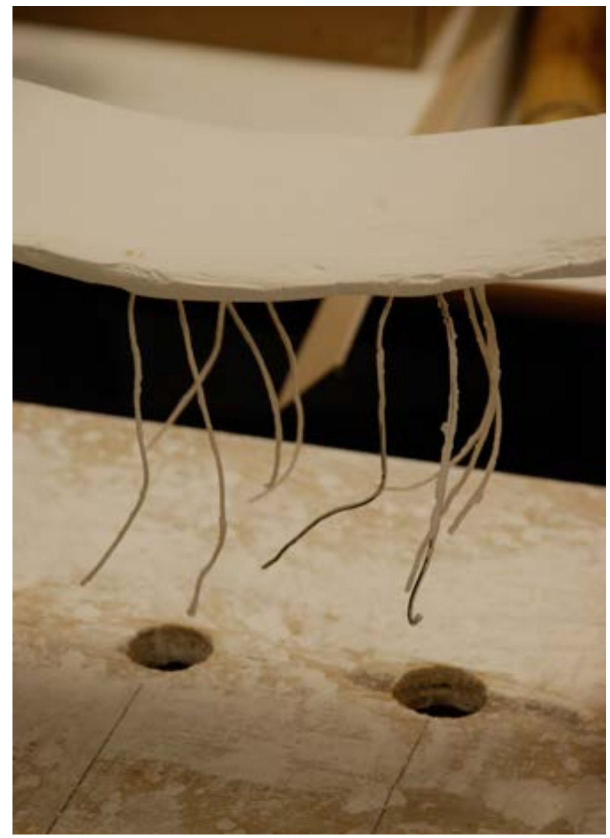
Model Construction







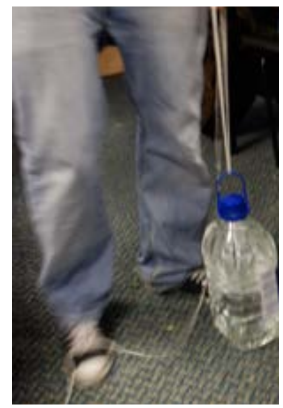
Using plaster and Plaster Hardener applied over 2 layers, making sure to cover the wire and cloth equally from both directions.



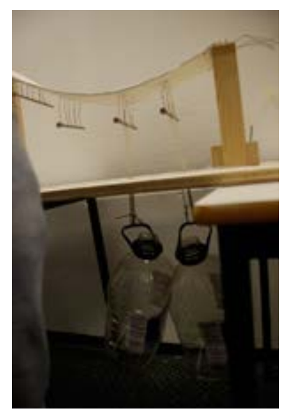
Cutting holes for suspended load to connect to loading wires.

Model Construction

We used solid nails to spread the load.

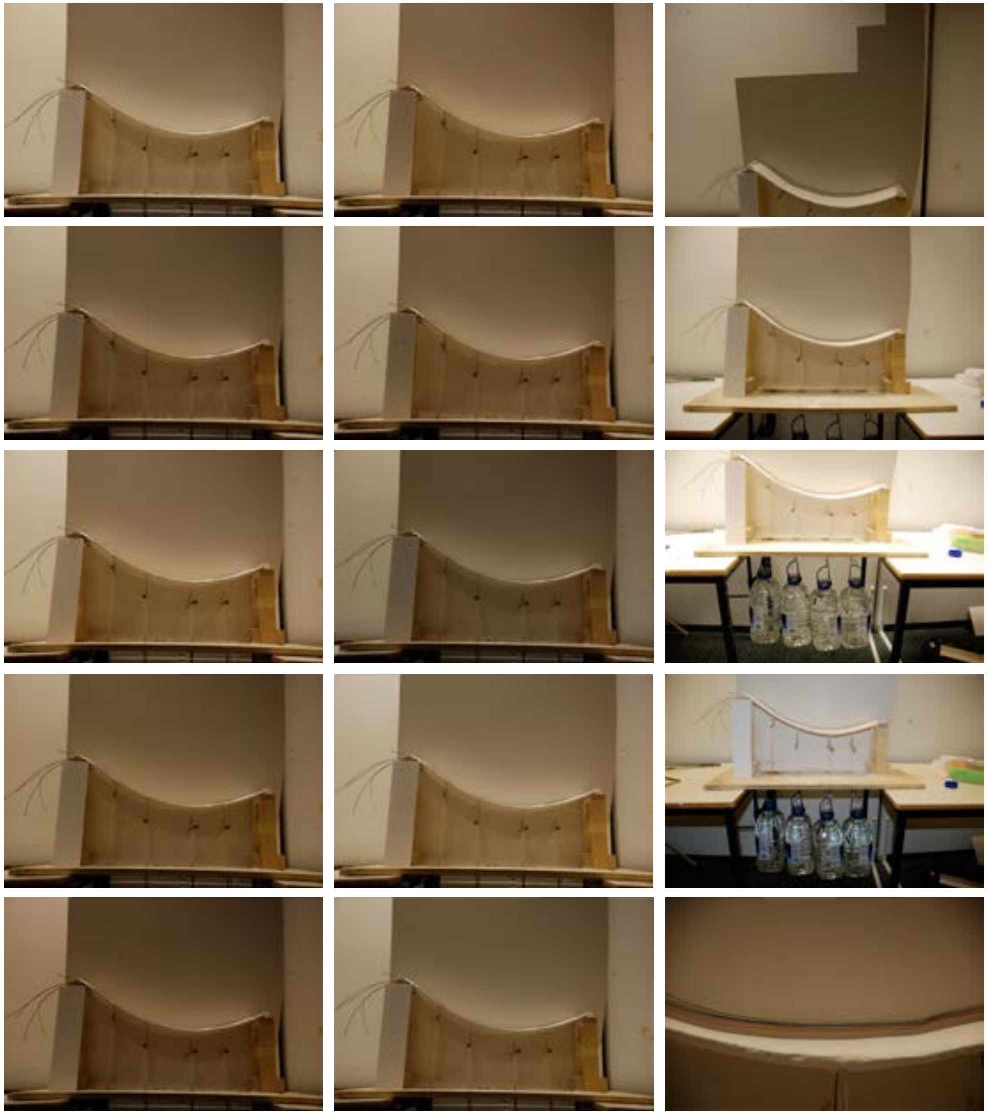


Using 4 x 5liter bottles of water for the 20kg required testing load
Initially water was removed.



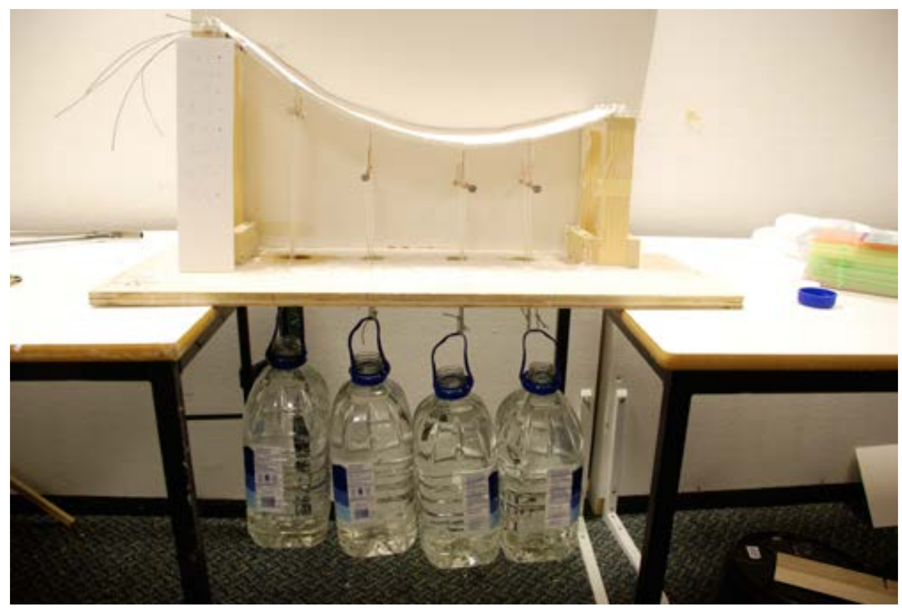
Using a large piece of card to record the deflection at increments of 0.5liters per bottle (2liters total load per incriminate) recorded using different colors

Model Construction



Using a large piece of card to record the deflection at increments of 0.5liters per bottle (2liters total load per incriminate) recorded using different colors

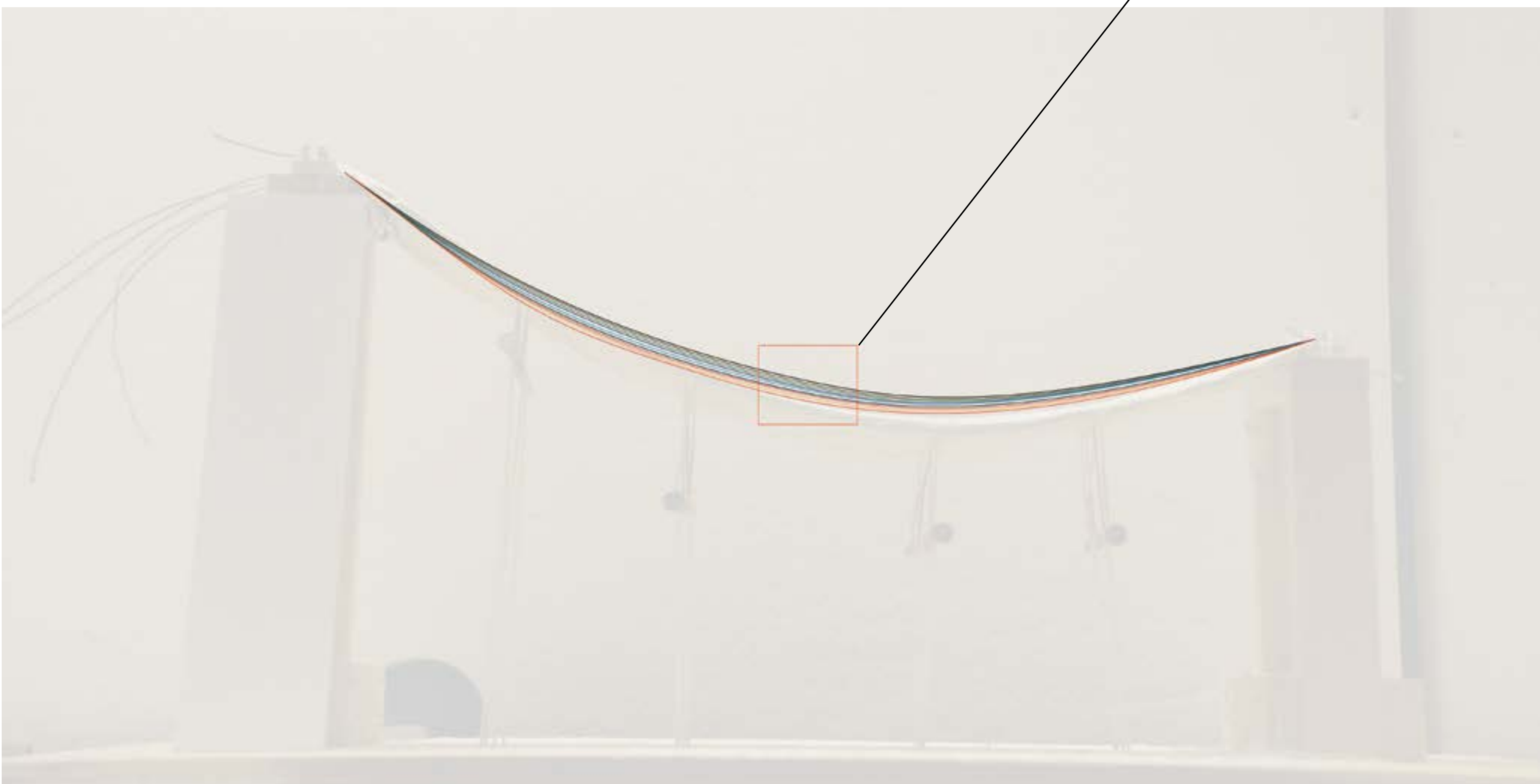
Result 20Liters = 20KG (= 0.196133KN) require load held with a deflection of 5mm/500mm = 1/100th



Roof Deflection During First Testing

Load on the Model: ~20KG (= 0.196133KN)
(Using the elasticity of plaster)

Initial curve of roof
Test 1 - 6 liters(1.5 litersx4)
Test 2 - 8 liters(2.0 litersx4)
Test 3 - 10 liters(2.5 litersx4)
Test 4 - 12 liters(3.0 litersx4)
Test 5 - 14 liters(3.5 litersx4)
Test 6 - 16 liters(4.0 litersx4)
Test 7 - 18 liters(4.5 litersx4)
Test 8 - 20 liters(5.0 litersx4)

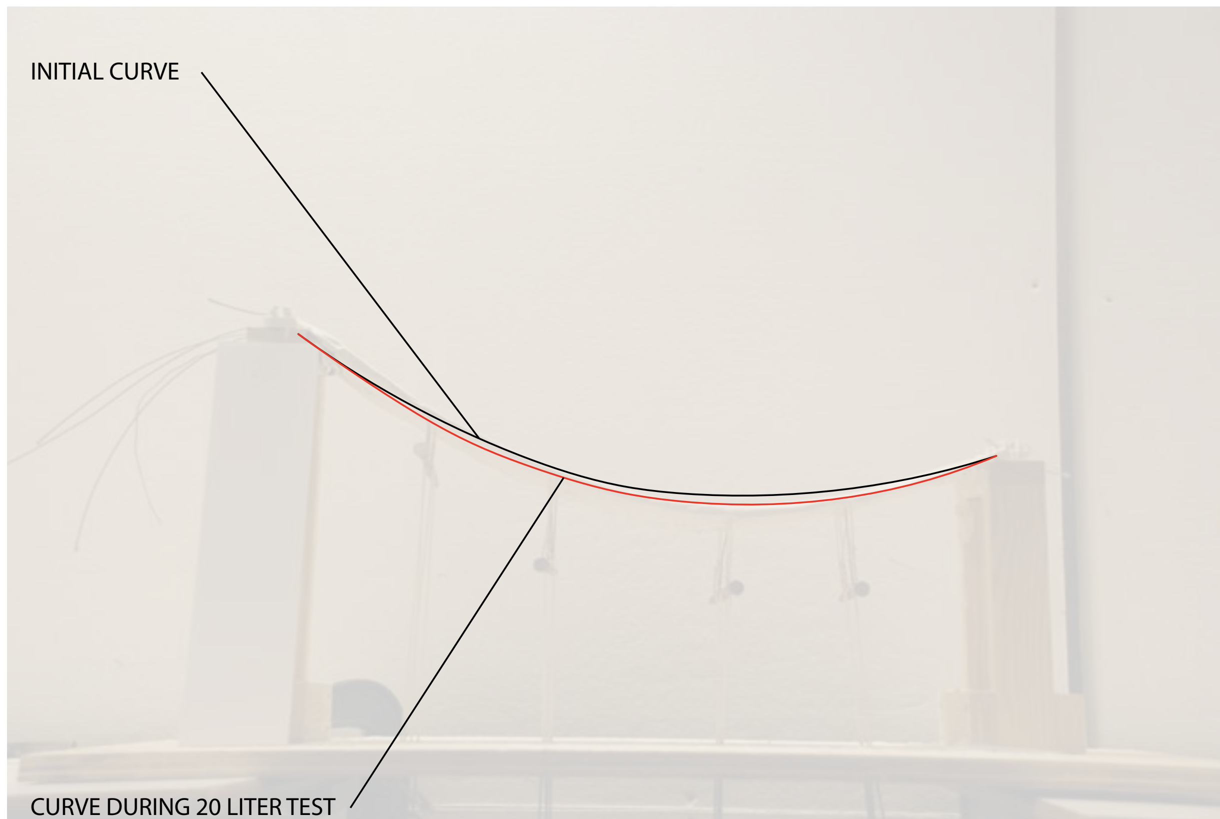


Roof Deflection of Model vs. Deflection of Prototype

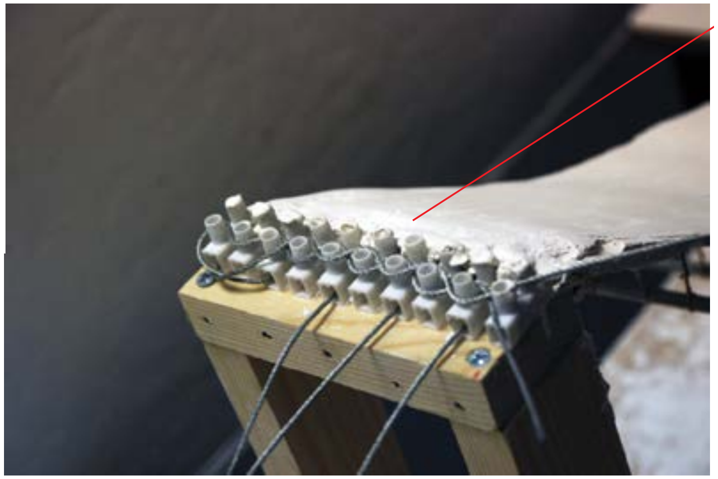
The deflection rapport of the roof structure of Dulles Airport 1/360, where 360 is the span of the roof.

The deflection of our model is 1/100.

Deflection during Test 8 - 20 liters

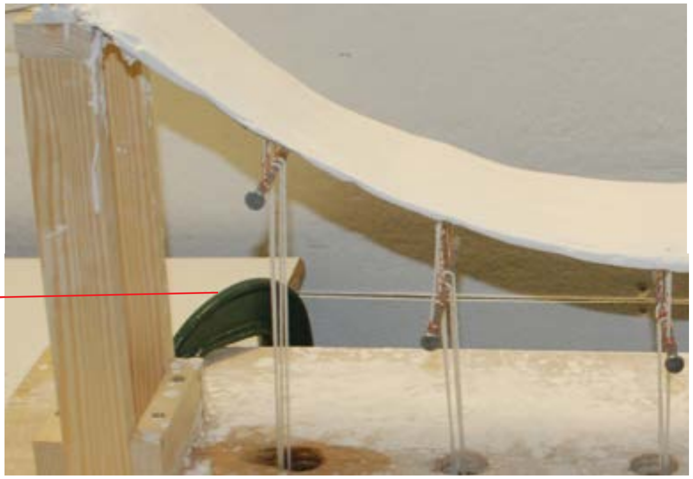


Cause of Additional Deflection in the Model (Conclusions after initial testing)



The Elasticity of plaster is 1/3-1/4 E of Concrete, but the Elasticity of steel is the same for both our model and the Airport

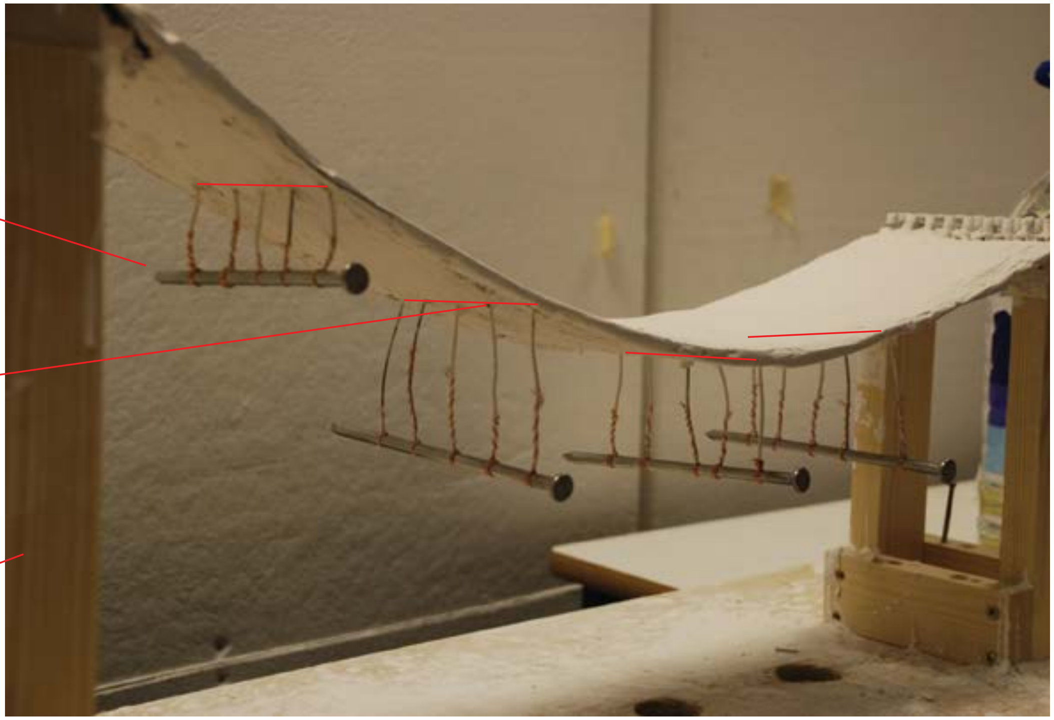
- We used clamps to counteract the deflection of the plywood base of the model:



- We used nails to distribute the load locally

- But the load is still localised in 4 main areas, not uniform across the model roof

- The columns of the model were not rigid enough and deflected slightly during testing



Further Testing and Failure of the Model:

Because we initally believed the load bearing capabilities of the plaster used in our model would affect the deflection and ultimate faliure of the model, we calculated the load using the Elasticity of plaster - which lead us to the conclusion that the maximum load we should test our model with is 20 KG/0.19KN.

However, upon further investigation on how our model and the structure of the airport behave under load, we noticed that since this is a funicular structure, a tension structure the dominant load we should be modelling is in the steel cables, which are used in both our model and the airport structure. We calculated our load for the second test according to the Elasticity of steel, which is the same in both structures.

Load on the Model: 20KG (= 0.196133KN)
(Using the elasticity of plaster)

Buckingham Π Theorem

$$\frac{W_m}{E_m \ell_m^2} = \frac{W_p}{E_p \ell_p^2}$$

E model = E plaster = $8 \times 10^9 \, N/m^2$

E prototype = E concrete = $30 \times 10^9 \, N/m^2$

$$\frac{W_m}{(8 \times 10^9)\, 0.4999^2} = \frac{113,832,132.6}{(30 \times 10^9)\, 49.99^2}$$

$$\frac{W_m}{E_m \ell_m^2} = 1.50503 \times 10^{-6}$$

$$W_m = (1.50503 \times 10^{-6}) \times 0.4999^2 (8 \times 10^9)$$

$$= 3008.86 N$$

$$M_m = 3008.86 \div 9.81$$

$$= 306.71 kg$$

If 306.71 kg is for the whole structure consisting of 15 bays,
Then for 1 bay, $\frac{306.71}{15} = 20.45 kg$

Load on the Model: 76.68 Kg (= 0.75 KN)
(Using the Elasticity of steel)

Buckingham π Theorem

$$\frac{W_m}{E_m \ell_m^2} = \frac{W_p}{E_p \ell_p^2}$$

Where $E_m = E_p$ = E steel cable $= 200 \times 10^9 \, N/m^2$

$$\frac{W_m}{\ell_m^2} = \frac{W_p}{\ell_p^2}$$

$$\frac{W_m}{0.4999^2} = \frac{112,832,132.6}{49.99^2}$$

$$W_m = 11283.21 N$$

$$M_m = 11283.21 \div 9.81$$

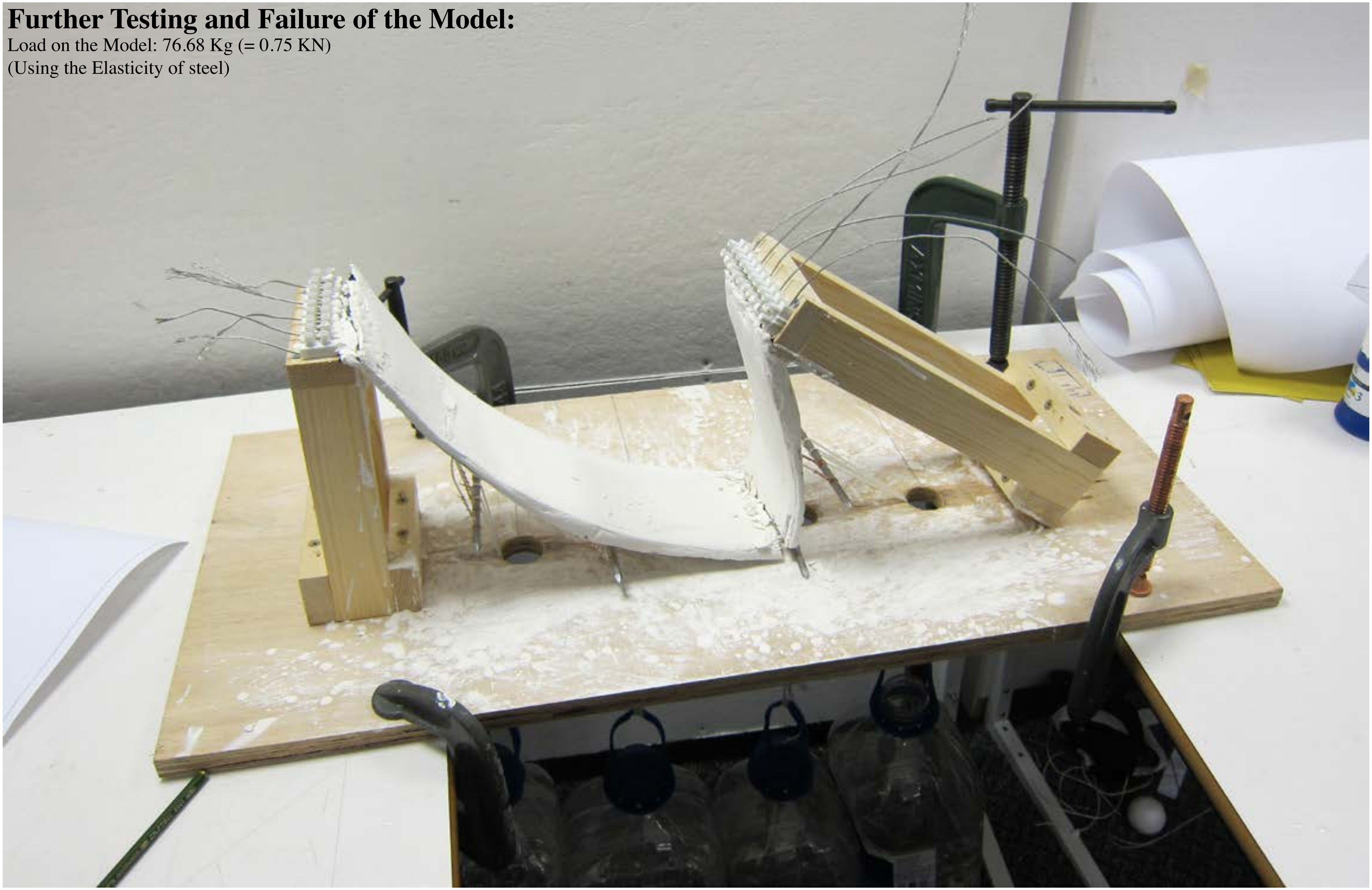
$$= 1150 kg.$$

If 1150kg is for the whole structure consisting of 15 bays, Then for 1 bay.

$$\frac{1150}{15} = 76.68 kg.$$

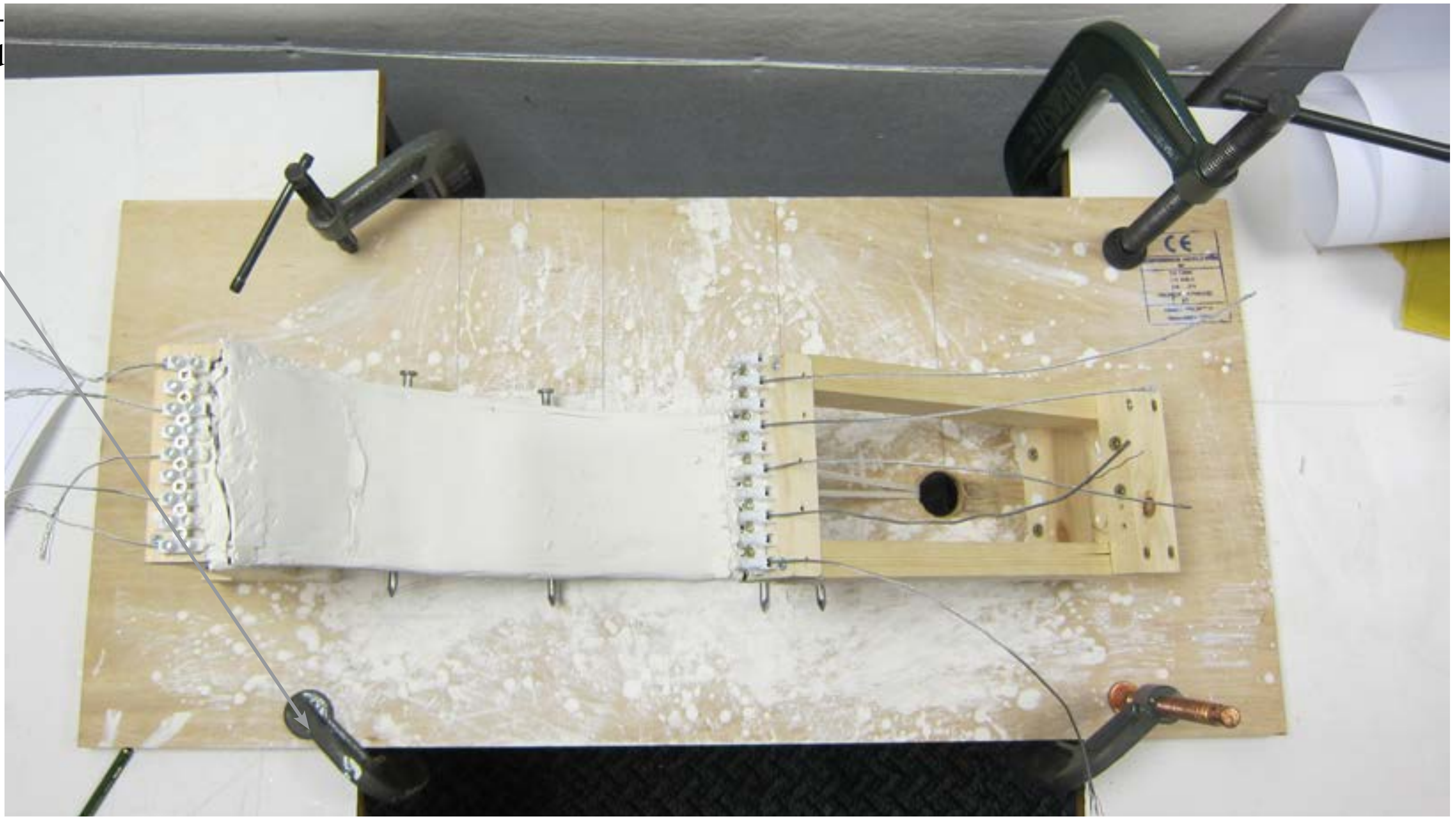
Further Testing and Failure of the Model:

Load on the Model: 76.68 Kg (= 0.75 KN)
(Using the Elasticity of steel)



Reasons for the Failure of our Model:

Allthough we used steel clamps to prevent deflection/buckling, the model ultimately failed our loading test



The structure failed at the level of the columns and load distribution points and the main resons for the failure of the structure are:

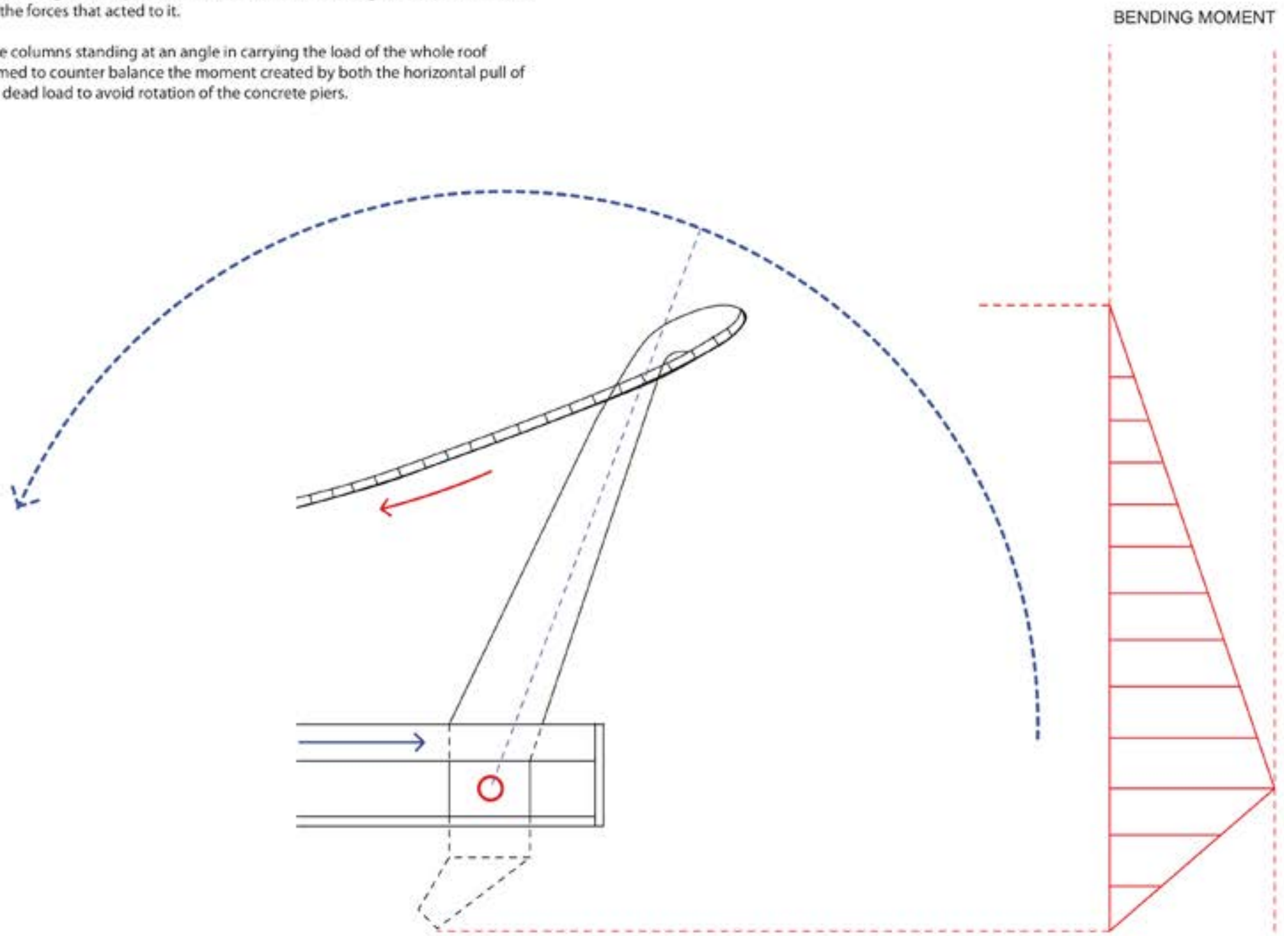
The base reinforcement of columns was not rigid enough, so the columns deflected and ultimately failed

The load was not uniformly distributed, which combined with the buckling of the cloumns led to the complete failure of the structure

Predicting Bending Moment and Compression force of the Column

Bending moment acted on the concrete piers is known to increase with distance away from the cable connection. Therefore the piers are designed to have a floor slab that act as compression to counter bending. In predicting the compression force on the base, bending moment is drawn and calculated to find out the forces that acted to it.

It is also found that the columns standing at an angle in carrying the load of the whole roof structure. This is informed to counter balance the moment created by both the horizontal pull of the cables through its dead load to avoid rotation of the concrete piers.



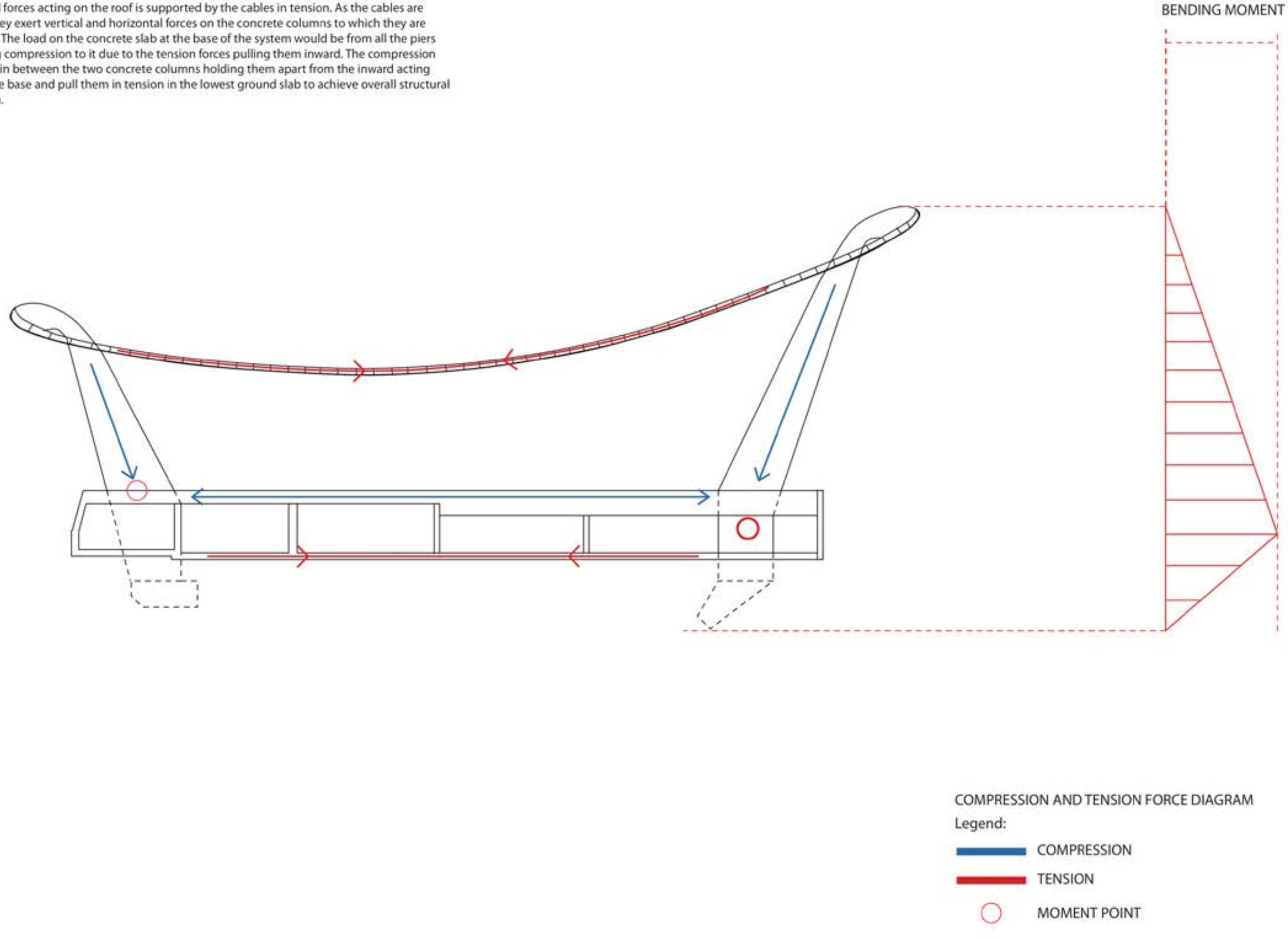
COMPRESSION AND TENSION FORCE DIAGRAM

Legend:

- Rotation
- Tension force
- Compression force to be calculated
- Moment Point

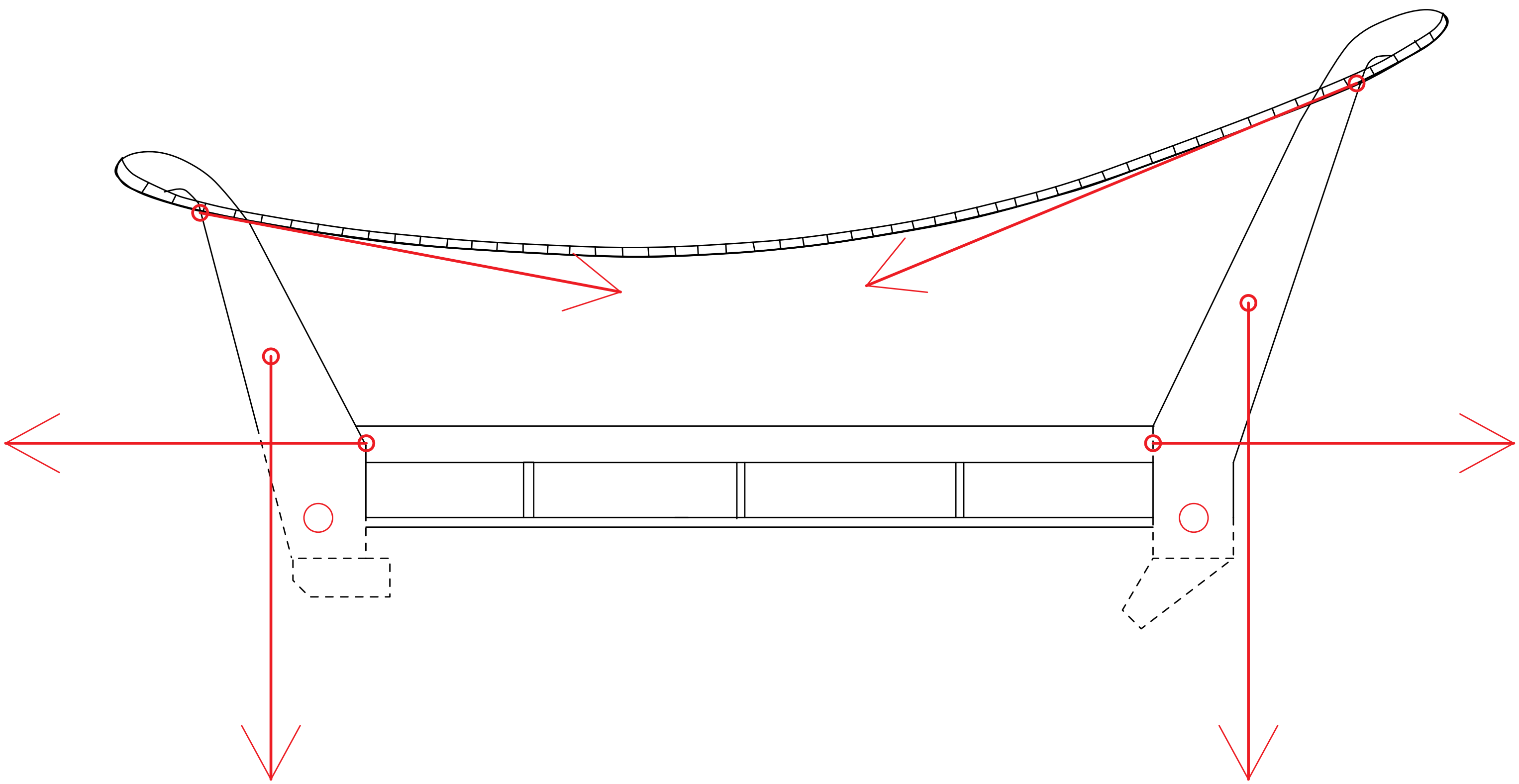
Predicting Structural Behaviour of the Overall Structure

The vertical forces acting on the roof is supported by the cables in tension. As the cables are stressed, they exert vertical and horizontal forces on the concrete columns to which they are connected. The load on the concrete slab at the base of the system would be from all the piers transferring compression to it due to the tension forces pulling them inward. The compression thus works in between the two concrete columns holding them apart from the inward acting forces at the base and pull them in tension in the lowest ground slab to achieve overall structural equilibrium.



Predicting Structural Behaviour of the Overall Structure

The resulting bending moment caused by tension forces of the cable and the self weight acting on the clolumn are pulling the columns to bend inwards, therefore the upper concrete floor in compression is pushing the columns outward, creating a bending moment counter to the bending moment of the tension forces in order to keep the whole structure in equilibrium.



FORCE DIAGRAM

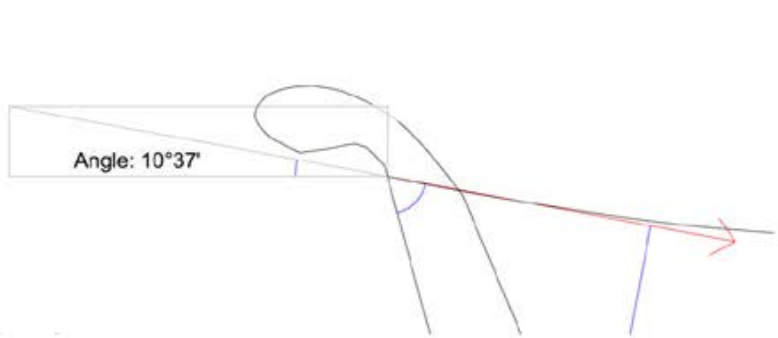
Legend:

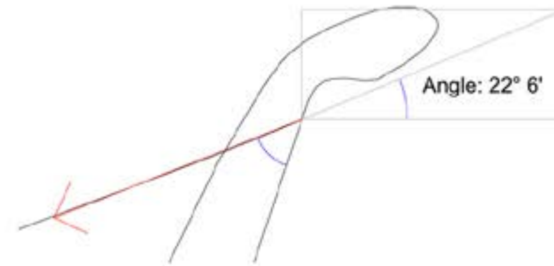
FORCE

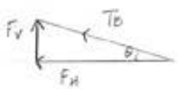
BENDING MOMENT POINT

FORCE ACTION POINT

Calculating Tension force and Bending Moment





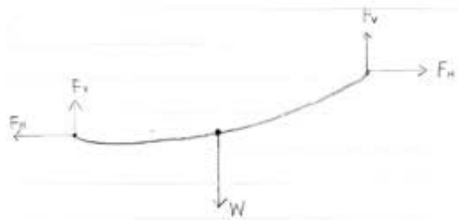


$\theta = 10°37'$

$T_B = \frac{W}{2\sin\theta}$

$T_B = \frac{F_V}{\sin\theta}$

$T_B = 13{,}020.49\ KN$



Weight of roof : 71,864,610.72N

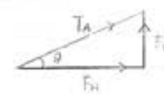
Weight of 1 Bay : 4790,974.04 N

$W = 4,791\ KN$

$W = 2F_V$

$F_V = \frac{W}{2}$

$F_V = 2395.49\ KN$



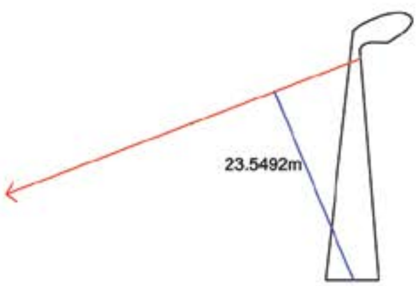
$\theta = 22°6'$

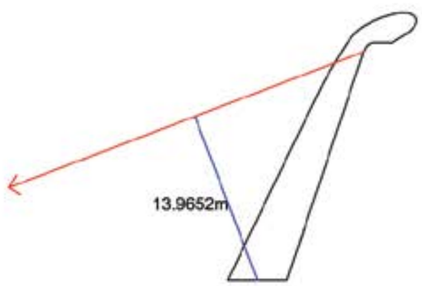
$T_A = \frac{W}{2\sin\theta}$

$T_A = \frac{F_V}{\sin\theta}$

$T_A = \frac{2395.49KN}{0.376}$

$T_A = 6364\ KN$





The inclined angle of the column decreased the distrance between the tension force and the bending moment point, it enables the roof to carry more load in this case.

Calculating Tension force and Bending Moment

$T_A = 6364\ KN$

$V_A = 227.43\ m^3$

$W_A = V \cdot \rho \times 9.81$

$W_A = 5355\ KN$

Equilibrium of Forces :

Bending Moment About X

Clockwise Moment = Anticlockwise Moment

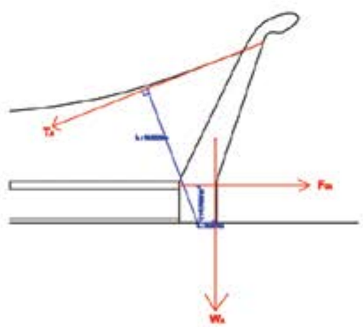
$$T_A \times L_{TA} = F_{CA} \times L_{CA} + W_A \times L_{WA}$$

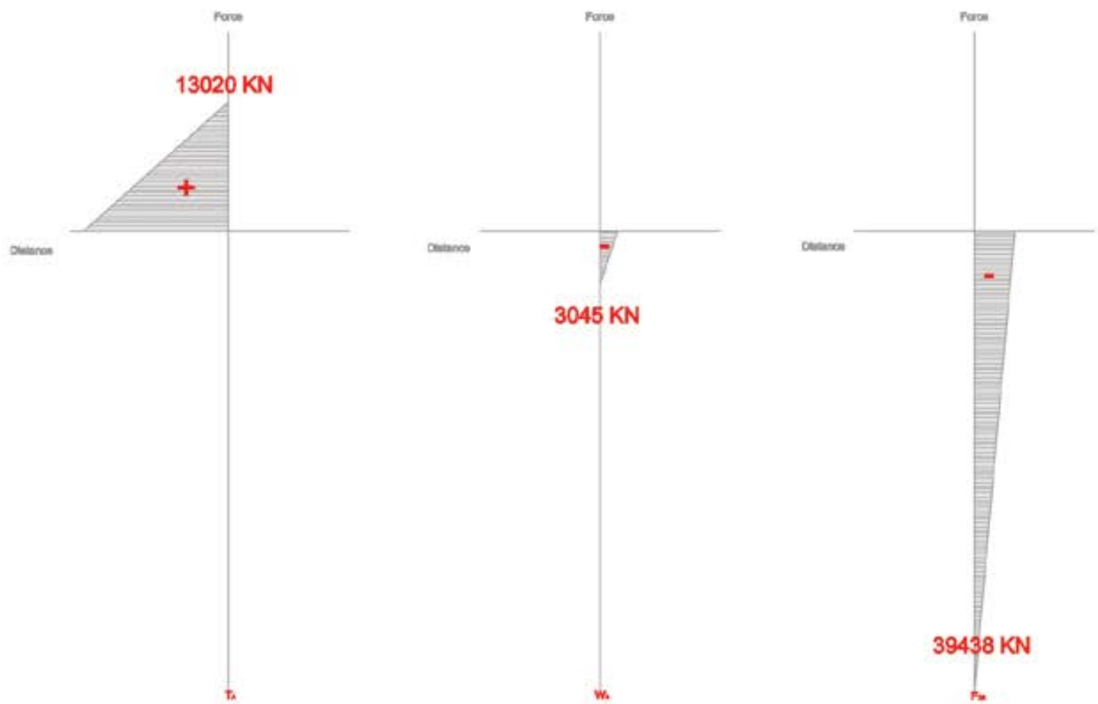
$$F_{CA} = \frac{T_A \times L_{TA} - W \times L_W}{L_{TA}}$$

$$F_{CA} = \frac{6364KN \times 18.32m - 5355KN \times 2.204m}{4.7493m}$$

$$F_{CA} = 22,066.020\ KN$$

Compression Force A: 22,066.020 KN





Bending Moment Diagram

Calculating Tension Force and Bending Moment

$T_B = 13,020.491\ kN$

$V_B = 129.34\ m^3$

$W_B = V \cdot \rho \times 9.81$

$W_B = 3045\ kN$

Equilibrium of Force

Bending Moment About Y

Clockwise Moment = Anticlockwise Moment

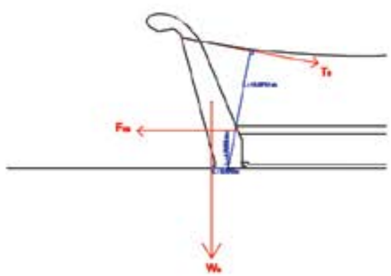
$T_B \times L_{TB} = F_{CB} \times L_{CB} + W_B \times L_{WB}$

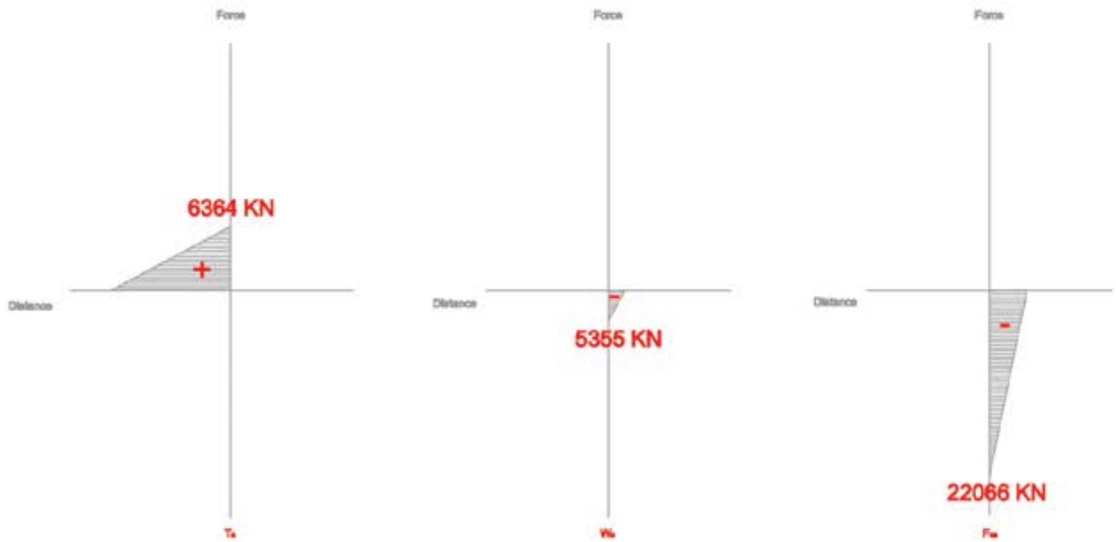
$$F_{CB} = \frac{T_B \times L_{TB} - W_B \times L_{WB}}{L_{CB}}$$

$$F_{CB} = \frac{193,633,064\ kNm - 6330.555\ kN \cdot m}{4.7493\ m}$$

$F_{CB} = 39,437.9\ kN$

Compression Force B: 39,437.9 KN





Bending Moment Diagram

Summary

The result of deflection in the model is higher than the prototype is due to:

Plaster used for the roof structure is 3 times more elastic and less stiff compared to concrete.

Steel purlins were not applied on the roof.

The Bending of the column are countered by:

Applying a narrowed angle to the Column structure.

Providing a wide base thus add more weight on the base.

The upper floor of reinforced concrete slab pushes the columns apart and pull them together at the bottom to achieve overall structural equilibrium.

Conclusion

In this building Saarinen manipulates an expression of tension and compression to give a dynamic energy to the structure in its walls and roof. The structure is clear to the viewer in how it works,

Bibliography

Books/Magasines:

Shaping Structures: Statics (Simplified Design Guides) [Hardcover]; Authors: Waclaw Zalewski, Edward Allen; Publisher: Wiley (1997)

Internet sources and articles:

(1) - http://www.usc.edu/dept/architecture/mbs/struct/Arch513/projects/dulles_airport_04.pdf-
Steel purlins were not applied on the roof.

Scans:

(2) - Figure 11.30 - *Shaping Structures: Statics (Simplified Design Guides)* [Hardcover]; Authors: Waclaw Zalewski, Edward Allen; Publisher: Wiley (1997)

NOTE:
Please see attached DVD for Submission PDF, Video footage and pictures of testing