ABSTRACT

DESIGN AND ENGINEERING OF A FABRIC STRUCTURE

JAIRO RIOS

Fabric structures are designed in an iterative process between architect and engineer, analysis input and output, and detail and patterning. There are three main steps in designing a fabric structure: shape finding, loading, and patterning/ detailing.

Shapefinding consists of finding the shape of the fabric where the fabric forces are in equilibrium. This type of structure is geometrically nonlinear which require iterative analysis to converge on a unique solution.

The loading of the structure is similar to that of any conventional structures. The departure is in the major effects that suction and ponding have on fabric surfaces.

Usually the details of a fabric structure are left exposed as an architectural element. The construction of the actual fabric requires the patterning of the fabric strips, that are heat welded or clamped together to form the shape of the structure. This initial "skin" can then be prestress to counteract the forces that it is subjected to.

DESIGN AND ENGINEERING OF A TENSILE FABRIC STRUCTURE

by
Jairo Rios

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by
Jairo Rios

Dr. William Spillers, Thesis Advisor | Date
Distinguish Professor of Civil Engineering
New Jersey Institute of Technology, Newark, N.J.

Dr. Ala Saadeghvaziri | Date
Associate Professor of Civil Engineering
New Jersey Institute of Technology, Newark, N.J.

Edward Dauenheimer | Date
Professor of Civil and Environmental Engineering
New Jersey Institute of Technology, Newark, N.J.

BIOGRAPHICAL SKETCH

Author: Jairo Rios

Degree: Master of Science in Civil Engineering

Date: May 1999

Undergraduate and Graduate Education:

- Master of Science in Civil Engineering
  New Jersey Institute of Technology, Newark, NJ 1999

- Bachelor of Architecture
  New Jersey Institute of Technology, Newark, NJ 1995

Major: Civil Engineering

To my loving wife Laura and
our family

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Thanks to Dominick Pilla and Craig Maloney, whom this thesis would not have the balance of the theoretical and the practical.

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CHAPTER 1

THE PROJECT

There are basically three steps for designing a fabric membrane structure(2):

1. Shape- Finding
2. Loading
3. Patterning/ Detailing

Usually in that order.

This project consisted of engineering a tension fabric structure for the Aladdin Casino. This report is written in the order of procedure used to analyze and design this fabric structure. The definition of what fabric structures are and how to analyze them are in Appendix A. I was initially given a set of architectural drawings (Figure 5.1-5.3.) The drawings show the general ideas the architect has for shape and size. Because of the geometrically nonlinearity of the structure it is virtually impossible to get the exact shape without a computer analysis for a project of this size(3). Here is where the design/ engineering part of the project begins.

From the architectural drawings I am able to determine the release conditions for nodes and members. These nodes and members will create a cable net that represents the fabric structure. The cable net is then input into an iterative nonlinear analysis computer program that will then converge. The result is the shape of the prestressed structure that is ready to be loaded. When loaded, I checked for overstressed fabric and resized the cross sectional area of the edge and ridge cables. With the geometry, forces and size, I was then able to proceed with the detailing and patterning of the fabrics' strips to form the membrane structure.

The scope of this project is in the shape finding-loading and only the detailing condition at node 2. I will not discuss the patterning in this paper, although this project is a real project in design phase and patterning will have to be performed in the future. I have done some limited comparisons of two grid types, a 10' x 10' orthogonal grid (Figure 5.4) verses one that is mostly radial (Figure 5.5). I have also compared the results of node restraints and commented on other aspects of the modeling of fabric structures.

CHAPTER 2

THE SHAPE

The 2 dimensional model (Figure 5.4) is the starting point for the analysis. I used a program called Larsa, which is specifically designed for nonlinear solutions that large deformations require.

2.1 Selecting a Cable Net

There are many types of cable net configurations you could use. The results forces should not be different[1]. The following are pros and cons for the cable net that I have chosen:

Pros:

1. A 10' x 10' orthogonal grid is easy to draw manually, and easy to input the coordinates for nodes.
2. With the orthogonal grid it is easy to compute and input the fabric prestresses. If I used the radial - like model (Figure 5.5), I would have to calculate, with estimation, the prestress for each triangular area for the vertical and horizontal members.
3. As opposed to the radial cable net, the 10' x 10' grid has less nodes and members to do the computations, allowing for a faster analysis. On a slow computer, this is important. The shape-finding part of the analysis sometimes requires that you to go back and forth, changing the prestress on the edge,

ridge and valley cables to get a shape that you find aesthetically pleasing. An architect might predefine this. If there is too much sag, you could increase the prestress to tighten it up. And inversely, if the cable is too straight or the output prestresses are too high you could reduce the initial prestresses to increase the sage.

4. I used a 10' x 10' grid due to the large size of the structure; the largest fabric strip is approximately twelve feet wide.

Cons:

In this case, the radial cable net will most likely be the actual patterning of the fabric strips. The final prestresses from the shape-finding of the 10' x 10' grid will have to be transferred to the a computer model of the radial cable net. This should produce a similar shape, to that of figures 5.6 and 5.7, where the displaced nodes can now be used to calculate the shape of each fabric strip.

2.2 The Shapefinding

The starting point of the shape-finding is a flat 2 dimensional structure. Here is listed the initial conditions that are input into Larsa. (In some programs you may not have the option or it may be difficult to control these parameters.)

2 Dimensional:

- With Larsa, I have found it more beneficial to start with a flat structure. The fixed nodes are the supports. The supports are fixed everywhere that the fabric is supported. After the shape is found, the supports for mast that attaches to the fabric is allowed to move during the loading. The unbalanced condition for the two dimentional structure is to vertically displacing fixed nodes to their final position. The final position is determined by the architectural drawings.

- For the first run it is recommended to have the Young's Modulus, E, as low as possible so that the cable net will change shape like a rubber band. The solution for displacements will be similar to nodal equilibrium. Since the Larsa program does not accept a value of zero for E, I used 1 psf. In a large deformation this makes a difference. Hence if you start off with the fixed nodes already displaced, the members connected with that node will try to maintain the original length as much as possible. The difference between the support nodes displaced, with the expectation that the cable net will bounce into place, and the support nodes moved incrementally into place can be very obvious. This will get the structure into a close approximation of the final structure and ready for a second run at shape-finding, if desired.
- The nodes that are not fixed will be free in the x, y, and z directions not just the z direction. Table 6.1 shows the results of the difference between two runs, the first run is having only z free and second trial is having x, y, and z free to displace. When free in all directions, from flat to shape, there is less of a difference from the maximum and the minimum forces on the individual cables. This is more advantageous since you would like a relatively consistent forces per cable, and the maximum forces are less than that of the "Only Z Free" trial.
- The prestressing of the fabric is 3000 lbs. in tension. Industry standards for prestressed fabric are 20 to 25 pound per linear inch (pli).

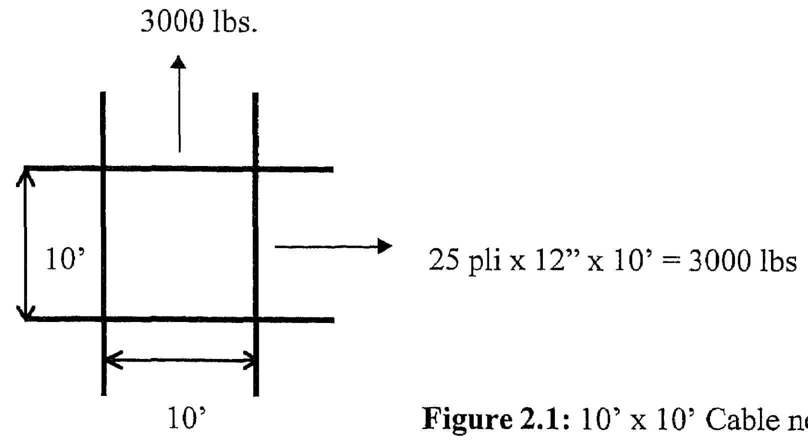


Figure 2.1: 10' x 10' Cable net grid

- The members are "Type = Cable", Larsa allows the user to define certain member properties, like Beam, Nonlinear Spring, etc. It also understands that a cable can not go into compression. If there is any compression the force in that member goes to zero.
- The edge and ridge cables are prestressed to 10 lbs in tension, to help with the convergence and displacement. For these cables, the Young's Modules is very high so the output forces on the cables will be the prestress for the loaded model. Larsa is able to easily control the E values for each cable. This helps in controlling the shape. If the cable looks too straight, i.e. not enough curvature in the cable, which is directly related to the amount of stress, or the output force is too high, the E can be lowered. If controlling the E is too difficult, try estimating the prestress by hand calculating the forces.

Example: Nodes A and B are fixed ends of an edge cable.

$$\Sigma M = 0 \quad \text{(eq. 2.0)}$$

$$\Sigma Fx = 0 \quad \text{(eq. 2.1)}$$

$$\Sigma Fy = 0 \qquad \text{(eq. 2.2)}$$

Solve this determinant structure using basic nodal equilibrium by taking $\Sigma M_B = 0$

$$R_A = 3000(x_F + x_E + x_D + x_C - y_F - y_D)/\,x_A \qquad \text{(eq. 2.3)}$$

The force in member AC is equal to the resultant force.

$$F_{AC} = R_A \qquad \text{(eq. 2.4)}$$

From the solution of equation 2.4 you can work your way back down the cable solving each member one at a time.

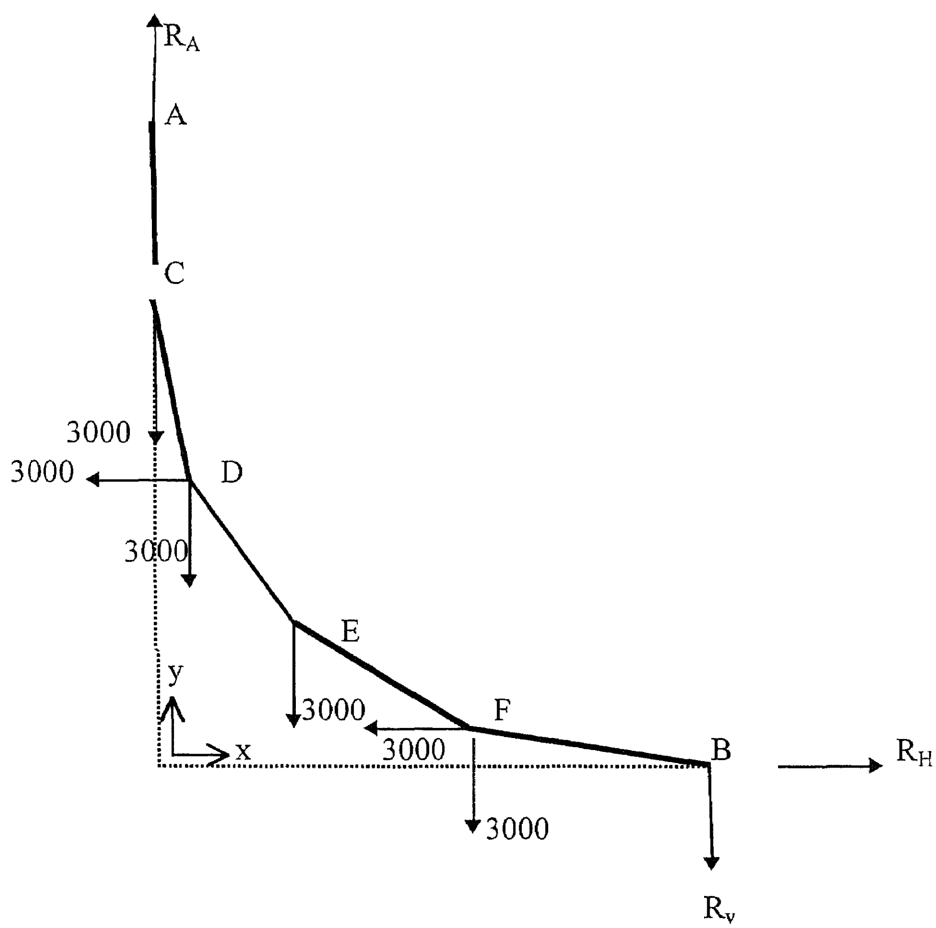


Figure 2.2: Solving Determinant Cable

An even faster rougher estimate would be to use:

$$\text{Maximum Tension} = WL^2/8 \qquad \text{(eq. 2.5)}$$

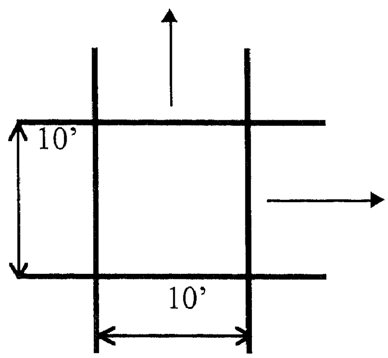
Where W = 25 pli, L = distance from A to B

2.3 Convergence

- I ran the output prestress for the second through fourth run to check for shape and convergence. I used the maximum output forces on the edge and ridge cables as prestresses for the proceeding run. I used 3000 lbs. prestress on the cable net for each run, which creates more uniform stress on the fabric membrane. For the loaded run, I used the prestresses in the edge and ridge cables as well as the outputted prestresses of the cable net as initial conditions.
- I used the displaced node coordinates from previous runs as initial coordinates for the proceeding runs.
- From the output edge and ridge forces of the first run, the cables can be sized, as seen in Table 6.4. The sizing is from Table 6.6, from AISI Steel Manual for cables. Table 6.5 is based on Zinc coated steel structural strand for Tons of 2000 lbs, this translates to a factor of safety of 2. I converted the forces from lbs. to kips and use the Class A Coated Inner Wires and Class C Coated Outer Wire's column. This chart is also used for the final sizing of maximum force in each cable after loading for detailing.
- For the second through fourth runs, I used a Young's Modules of 8000 pli for the cable net and 29,000 ksi for the edge and ridge cables.

- The cross sectional area of the members in the cable net has to represent the fabric.

120 lin. in.



10' x 12" = 120 linear inches

Figure 2.3: 10 x 10 Fabric Representation

2.4 Results

The results are on Tables 6.2 and 6.3. On Table 6.2, the last entry is the Cable Net. You can see from trial run to trial run that the cable net forces are becoming more uniform. This is due to continually using 3000 lbs. of prestress for each run as opposed to using the previous run's output. The check for convergence in listed on Table 6.3. The nodal displacements are not shown but they converged to .06 inch maximum displacement by the fourth run. I could have stopped at the third or even second run to load the structure.

Larsa does not have an option to create facets for you or finite elements. I manually inputted the three node elements. The final results become the shape of a fabric membrane structure. From here I am able to load the structure.

CHAPTER 3

THE LOADING

The industry standard for loading fabric membrane structures, normal to the surface, is to use 20 psf up and 20 psf down. With the Larsa program, I created very thin three node elements and used "pressure loads" acting at the centroid of the element. I input the thickness of the element as .001 inches. The second column in the output data is checking for shape again. The finite elements added some stiffness to the fabric membrane and this is the reason for checking shape. I set the E value for the elements so that the second column would be similar to the first column, the initial prestresses. Larsa also has four node elements.

3.1 Checking for Over-Stressed Fabric

The allowable stress on the fabric is 720 pli., with a factor of safety of 4, the factored allowable stress is 180 pli.

720 pli. / 4 = 180 pli (factored allowable)

The maximum force on the cable net from (Data 2) is 3810 lbs. The "represented area" of the cable net is 10' x 12" = 120 linear inches.

3810 / 120 = 31.75 pli

31.75 pli < 180 pli

Hence the fabric is not over-stressed.

If the fabric was overstressed by a small amount, 10% to 15%, a fabric reinforcing strip could be used to strengthen the fabric. Usually the higher stresses are at the support nodes and where the fabric is pulled, which is usually a mast or peaks. Another alternative, if the fabric stress exceed allowable tolerances, is to add cables; ridge and valley cables.

3.2 Checking for Compression

In the data on the analysis, you will see five columns: member numbers, the initial prestress, no load (for checking shape), 20 psf down, and 20 psf up. On the first run (Data 1), five cables members went into compression, so I raised the prestress on those cables, On the second run (Data 2) there were no members in compression.

CHAPTER 4

THE DETAILING

4.1 Developing Details

The detailing of a fabric structures are basically similar; a cable going into a pin connections, onto a metal plate bolted to a concrete abutment or welded to a metal pipe. The fabric is connected to an aluminum edge that is connected to the edge, ridge or valley cables (Figure 5.8-5.9).

The edge and ridge cables are again sized (Table 6.5) for diameters based on the maximum forces of Table 6.6 for all cables. The differences of Strand verses Wire Rope are enumerated in Appendix C, also from AISI Steel Cable Manual.

Like a syringe, the two center masts will prestress the fabric and cables. Bridge sockets are also connections that can perform prestressing. I chose to use closed sockets or as "The Crosby Group Inc." company would call it "open spelter socket." From Crosby Fitting catalog, I chose the typical grooved open spelter sockets (chart in Appendix D). I find the corresponding structural strand diameter for the socket dimensions. The dimensions correspond to the diagram in the upper right hand corner.

From the size of the pin and the calculated forces I am able to calculate the boss plate and plate sizes. These are calculated on the Connection Plate Sizing Calculation spread sheet 1 through 3 for the three cables that join at node 2. The connection sizing was done on the standards of the Allowable Stress Design manual. There are standard details for similar connections that can be found in much fabric membrane structure literature. From this spread sheet I then design and draw the details of the connection in plan (Figure 5.8) and the side view of the ridge cable RC - 2. The other cable connections are very similar. Much of the cost is in the costume details. So the more repetitive, the better.

4.2 Fortran Program

A Fortran program was written (Appendix E) using the formula for the cross product for a matrix. I multiplied two times the summation of the cross product for each elements to calculate the surface area. This is required to get the quoting price on the fabric quantity.

CHAPTER 5

FIGURES

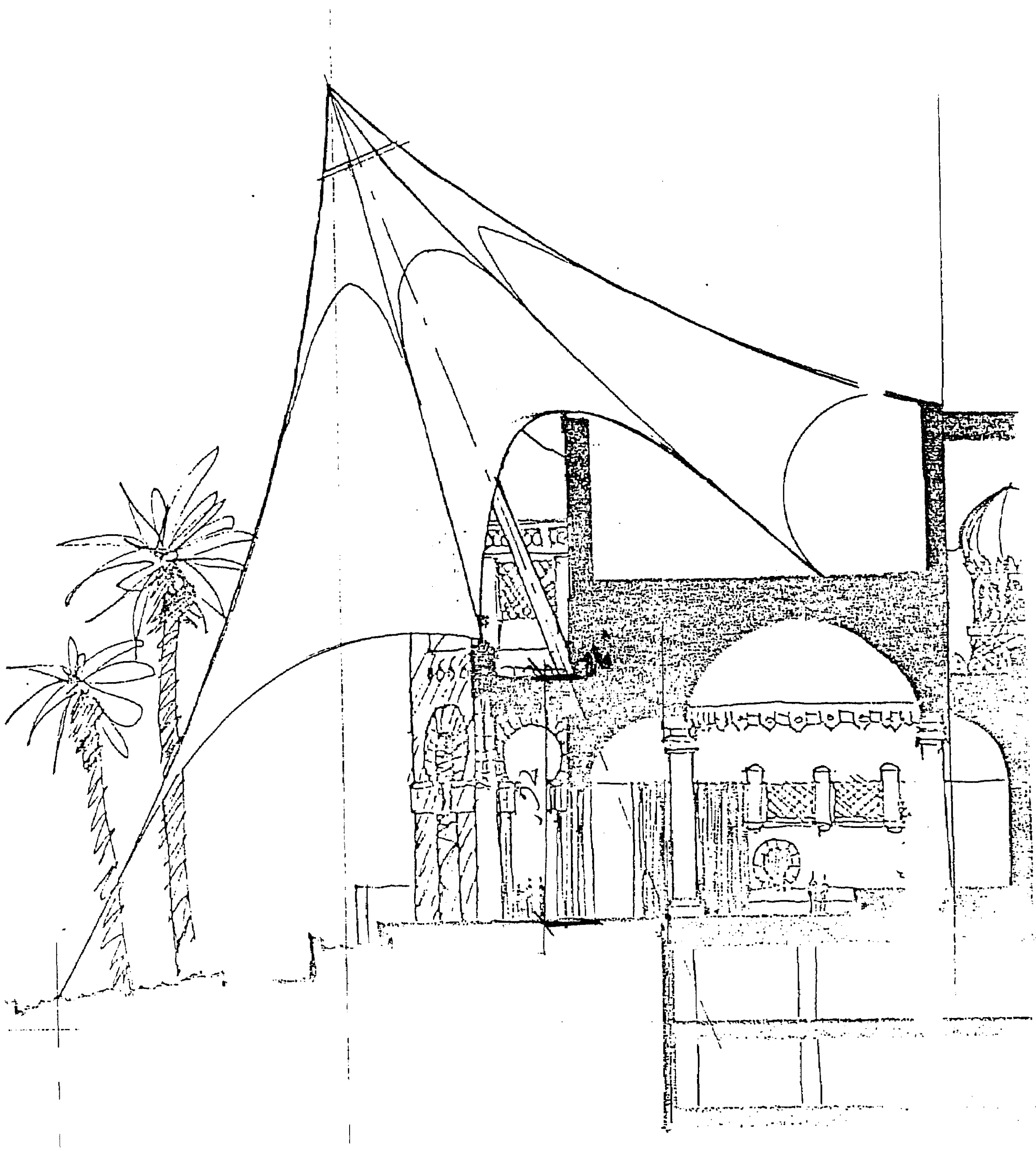


Figure 5.1: Side Elevation

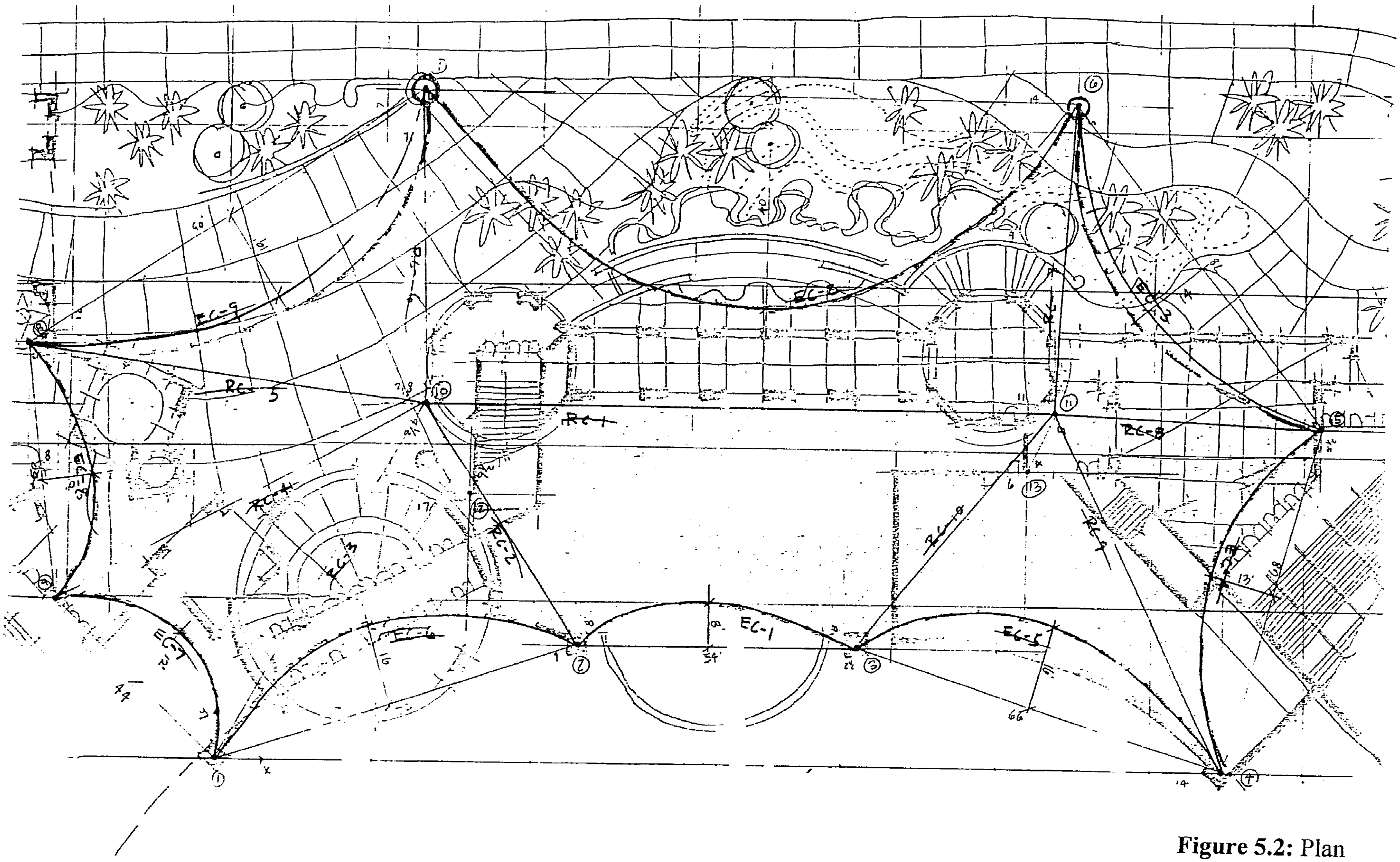


Figure 5.2: Plan

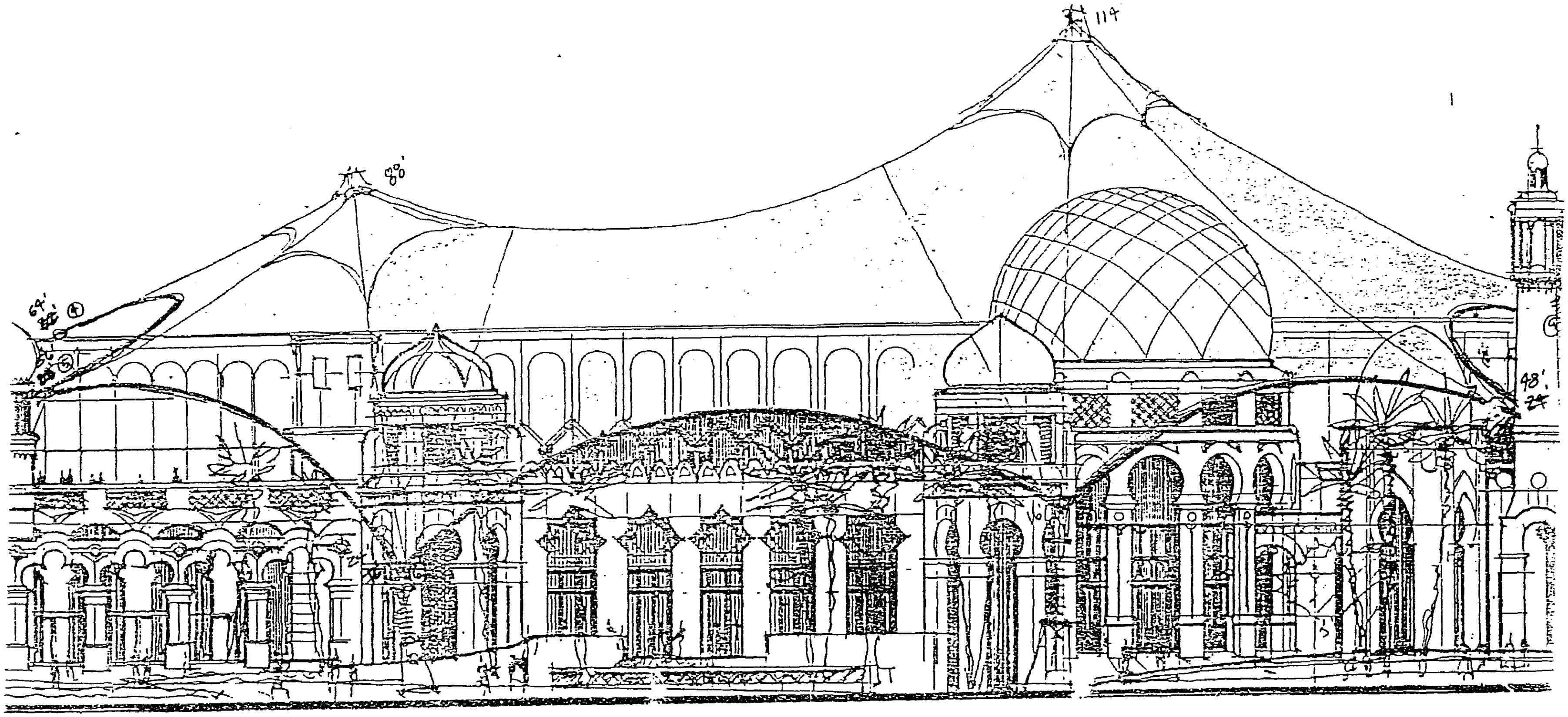


Figure 5.3: Front Elevation

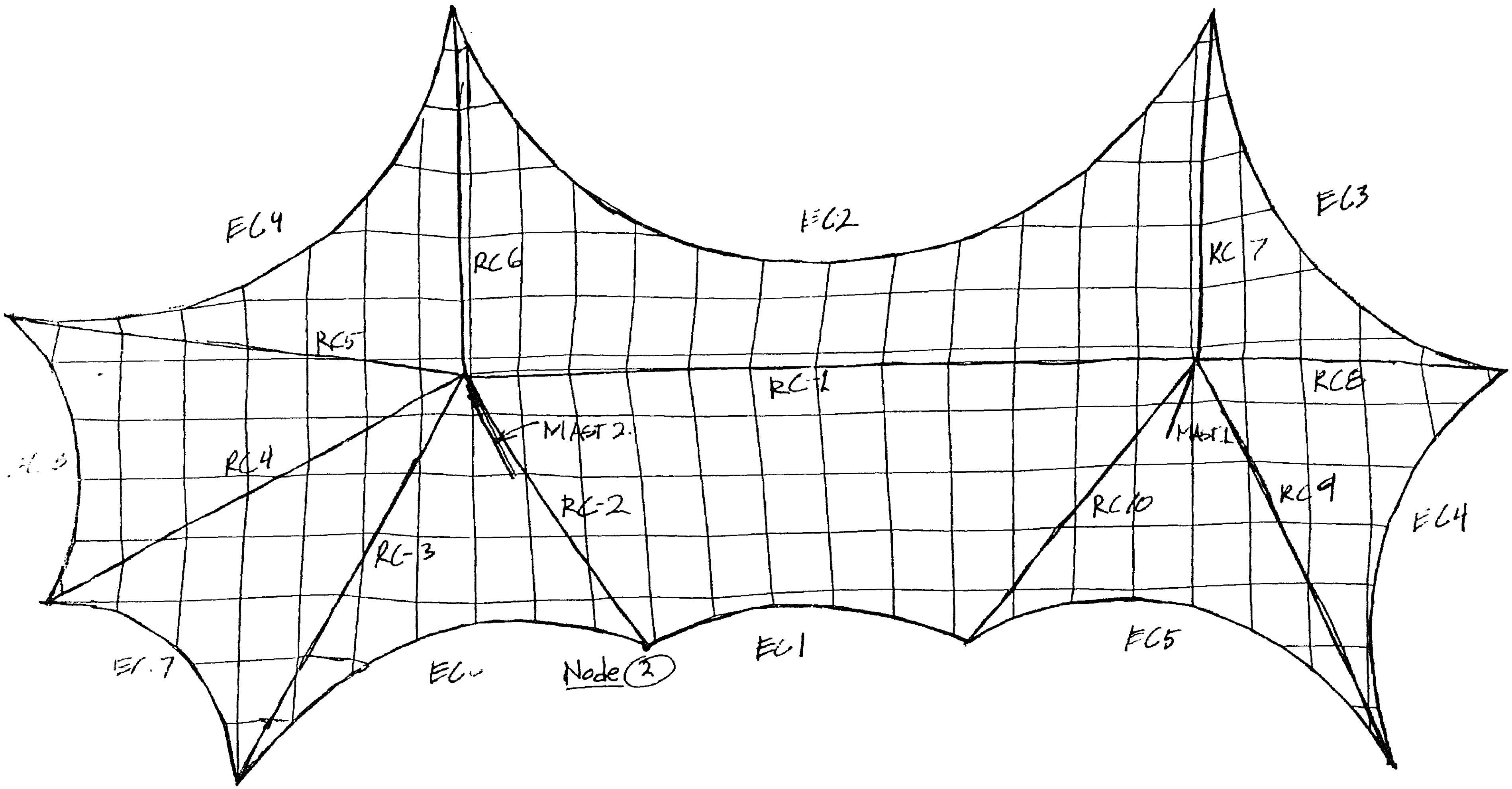


Figure 5.4: Computer Model, Orthogonal Grid

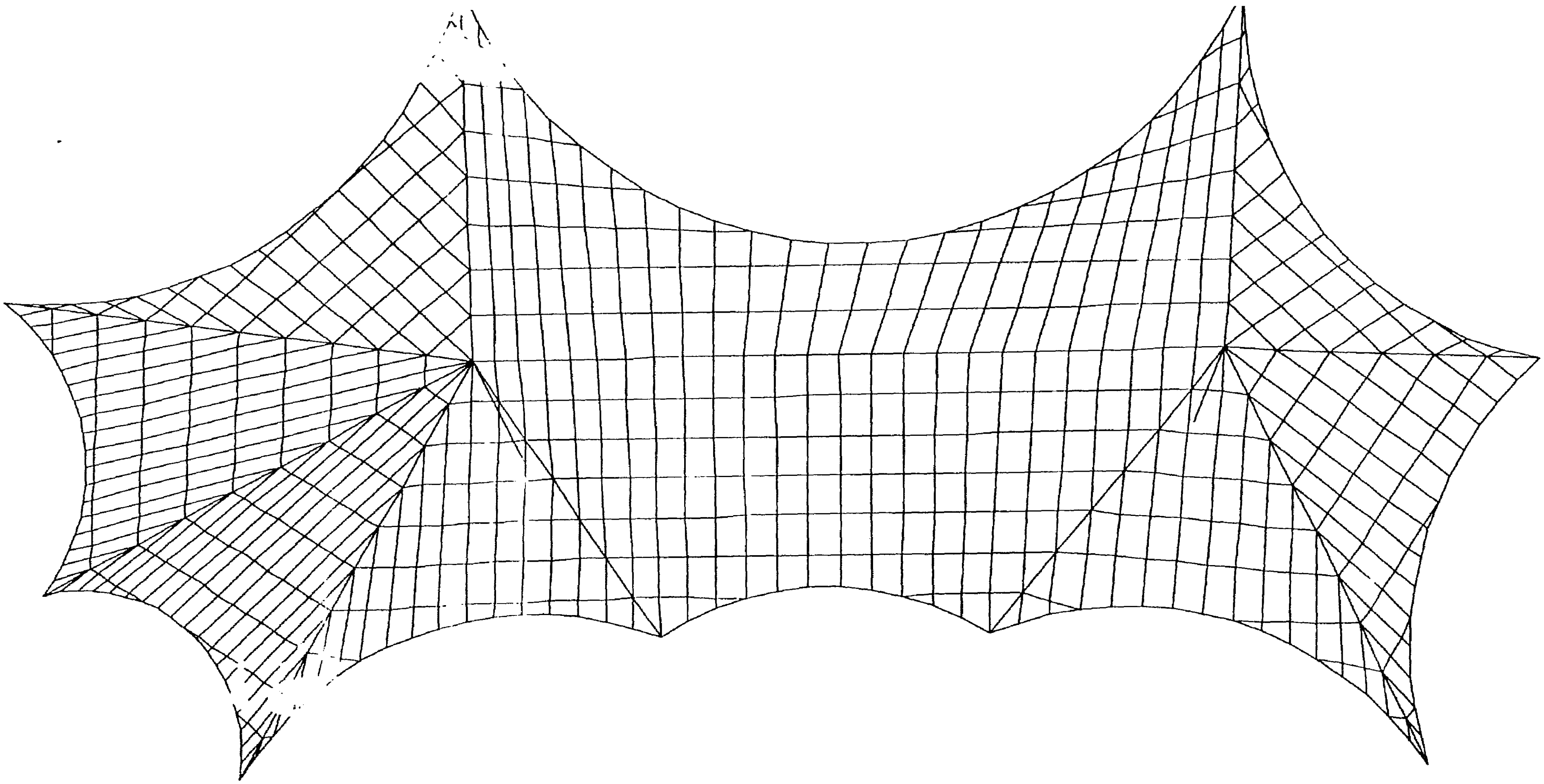


Figure 5.5: Computer Model, Radial Grid

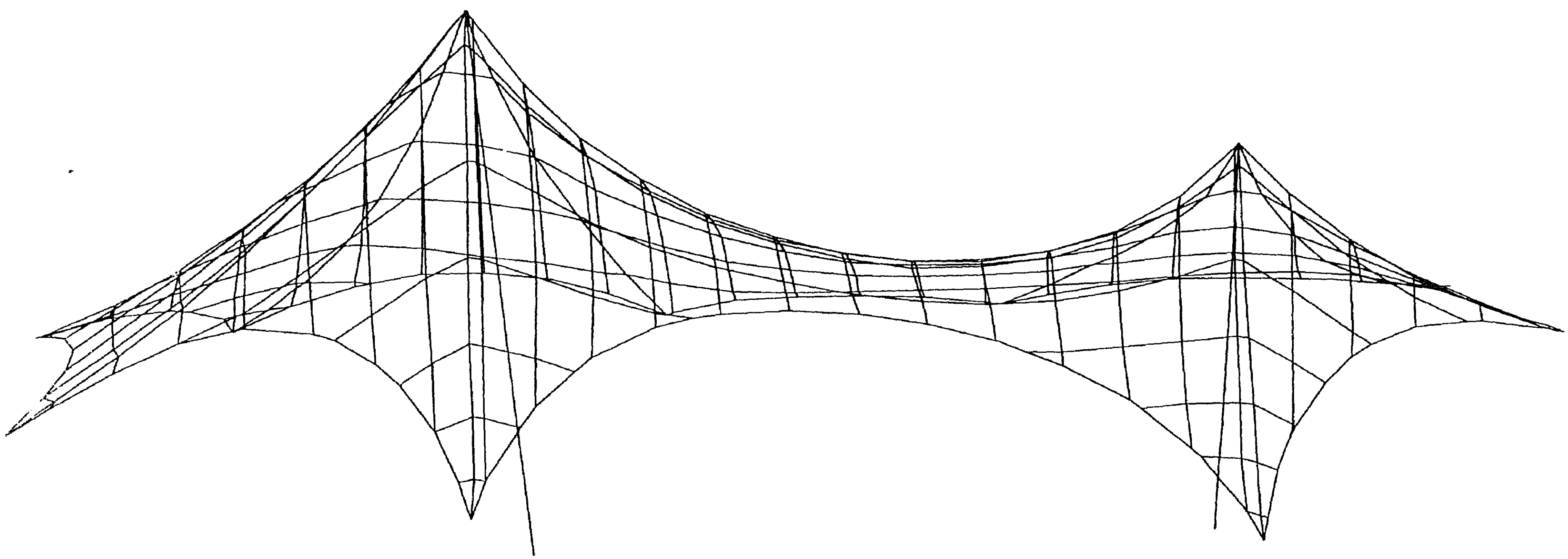


Figure 5.6: 3D Shape, Elevation

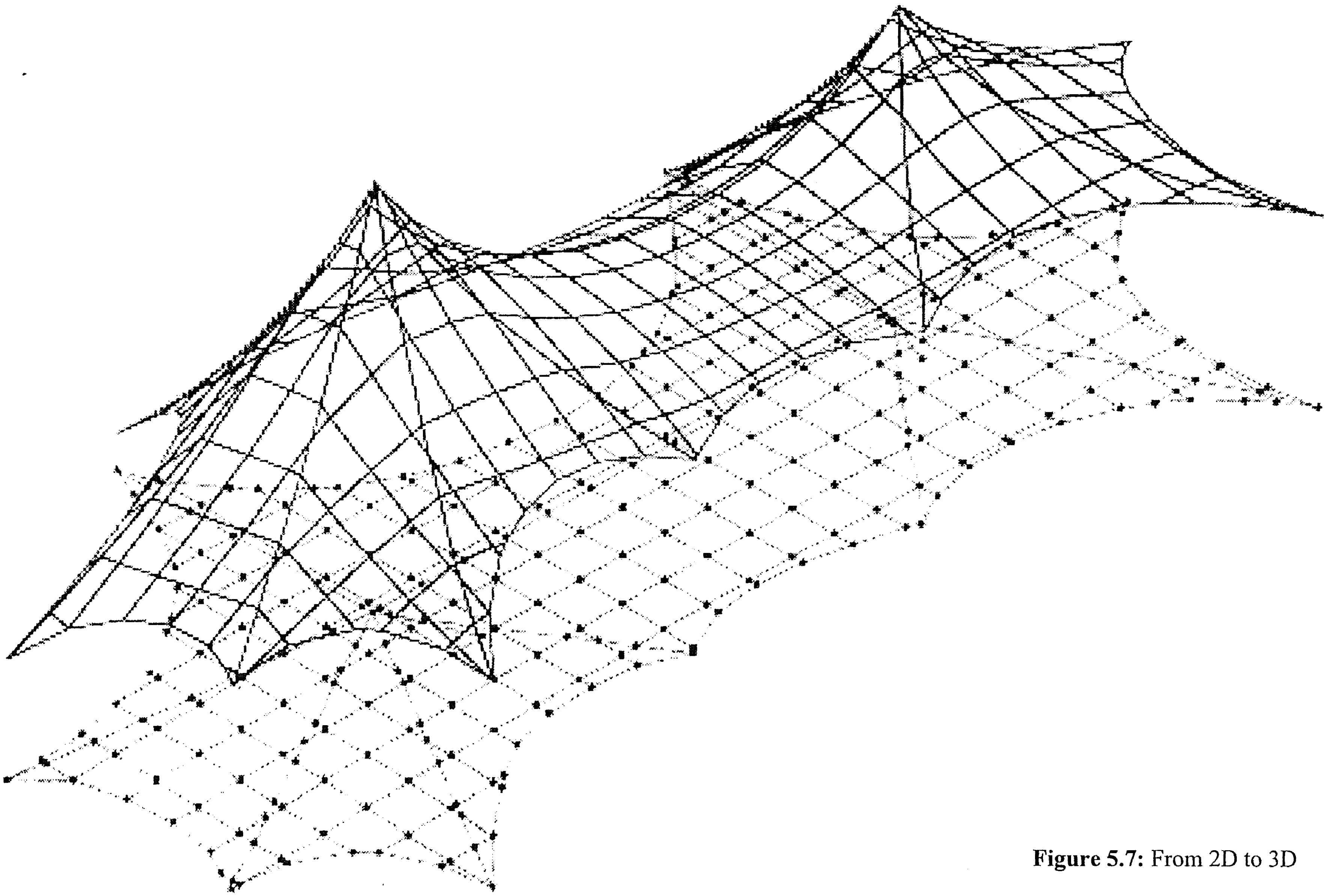


Figure 5.7: From 2D to 3D

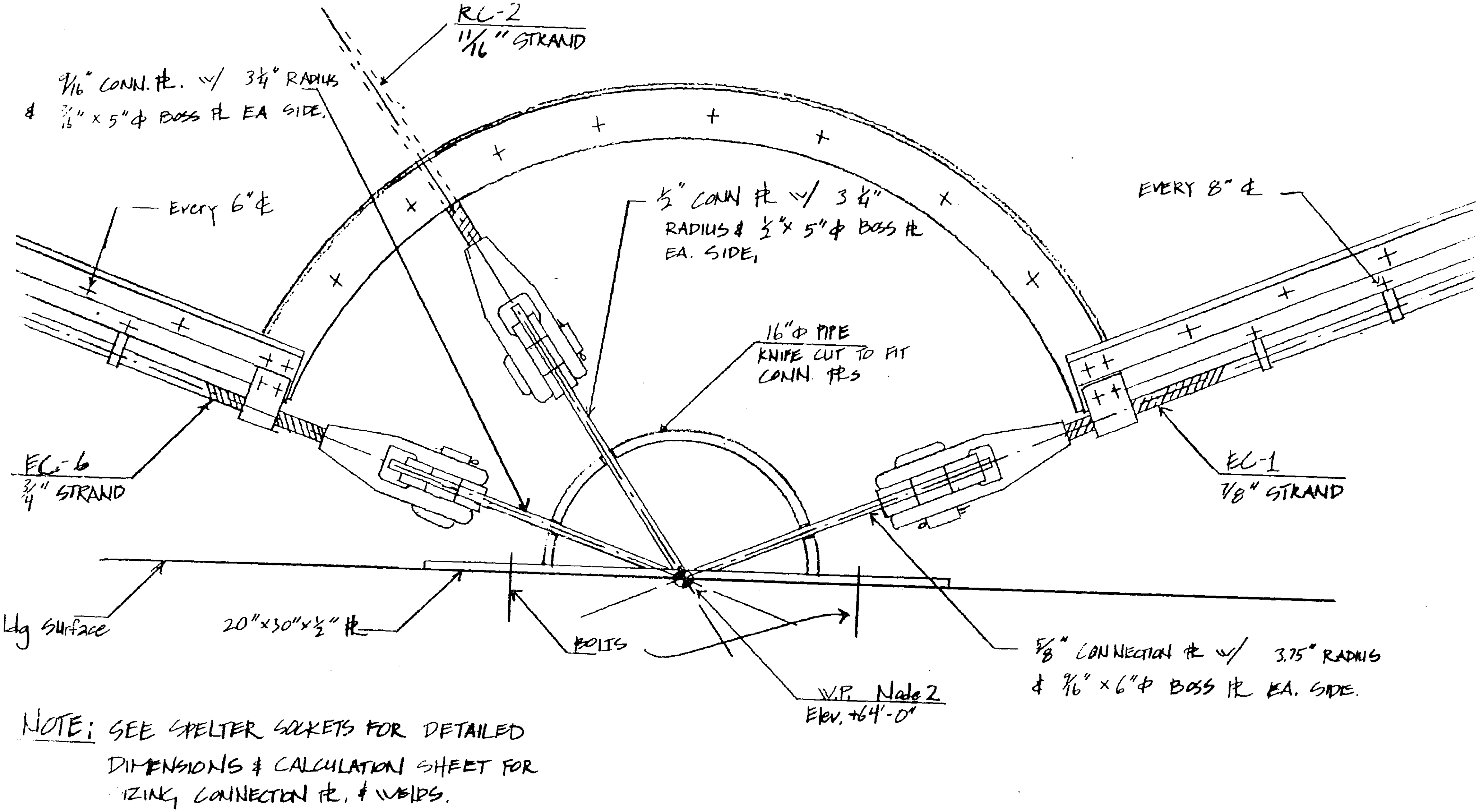


Figure 5.8: Detail Plan for Node #2

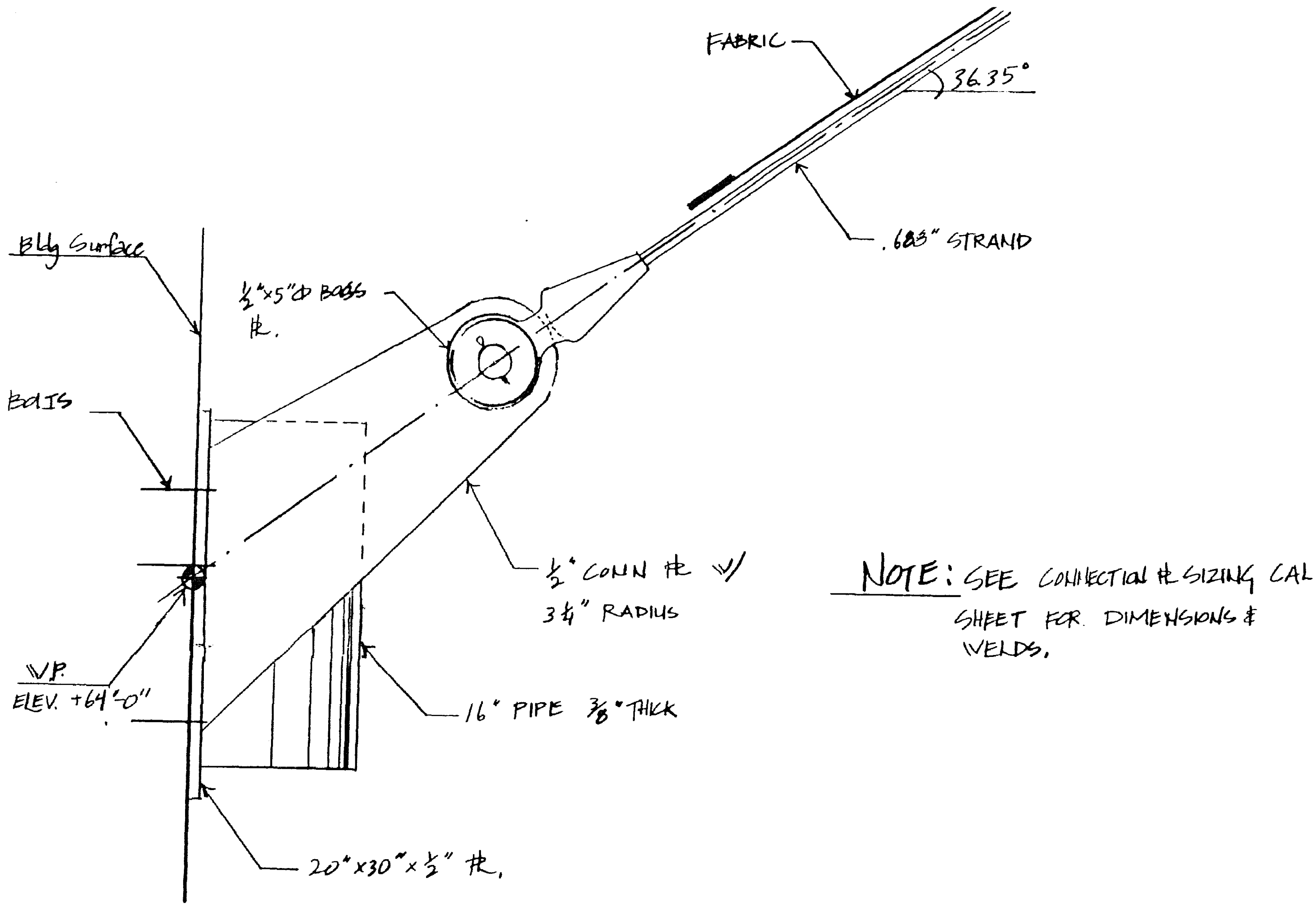


Figure 5.9: Detail Elevation for Node #2

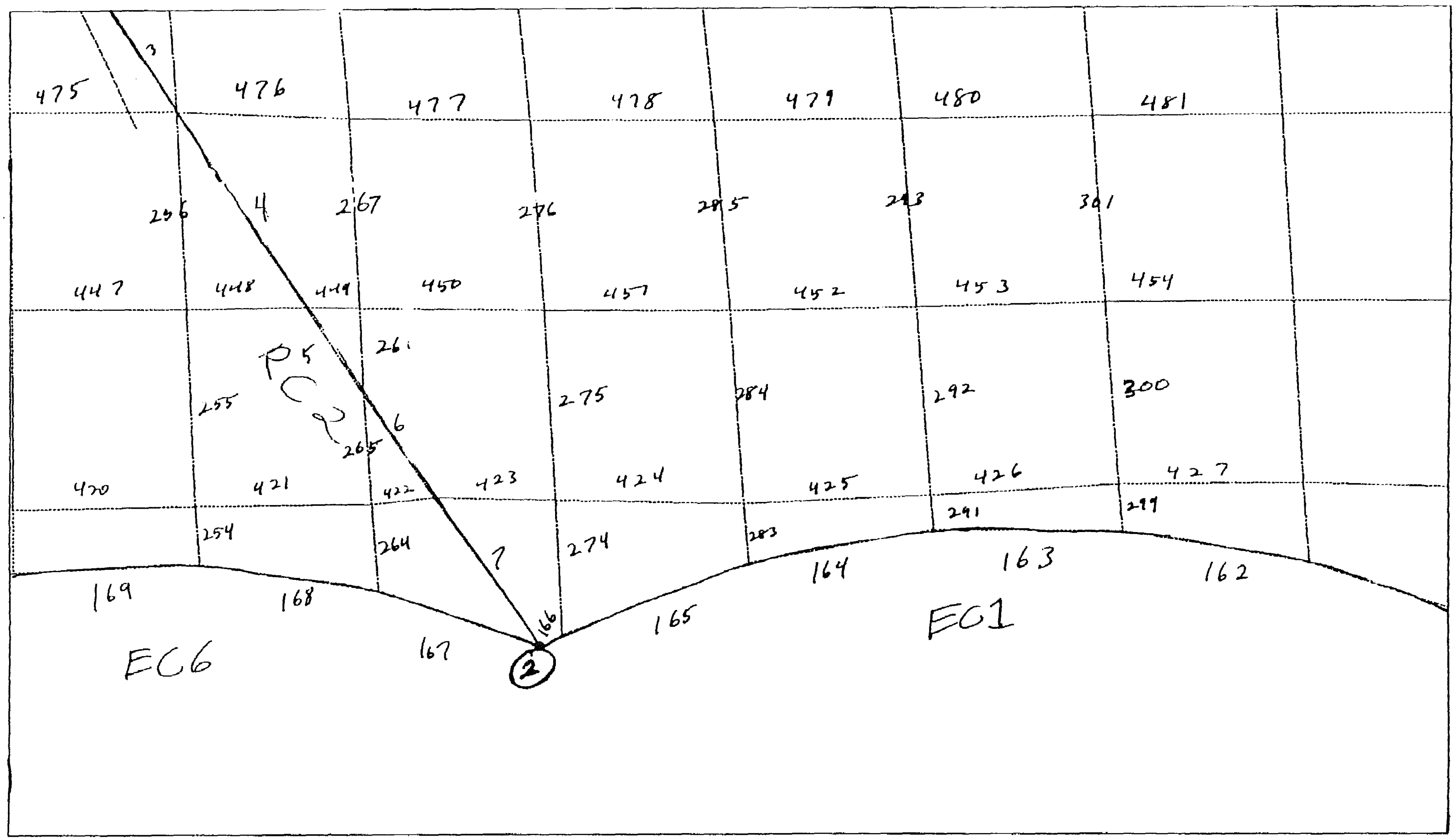


Figure 5.10: Member Map at Node #2

CHAPER 6

TABLES

Table 6.1: Variable Restrictions on Nodes

Maximum and minimum cable forces (lbs.), when X and Y movement are restricted versus when free in all directions.

Cables	Members	Only Z free		X, Y, and Z free	
		max	min	max	min
RC2	1-7	-8422	-2958	-8132	-3462
RC3	8 - 17	-6657	-450	-6109	-1021
RC4	18 - 28	-33964	-7231	-28486	-16402
RC5	29 - 36	-49482	-23832	-45223	-28307
RC6	37 - 73	-14031	-3025	-14009	-3170
RC1	44 - 57	-55659	-2690	-40810	-15948
RC7	58 - 64	-10797	-2426	-10583	-2506
RC8	65 - 70	-32385	-8211	-27199	-16476
RC9	71 - 77	-4125	-23	-3271	-270
RC10	78 - 85	-3952	-408	-3156	-680
EC7	86 - 91	-16107	-3031	-12330	-8276
EC8	92 - 97	-24846	-1324	-16114	-10907
EC9	98 - 108	-32563	-5911	-26016	-15093
EC2	109 - 128	-38287	-3810	-30169	-17068
EC3	129 - 140	-37201	-344	-28984	-16944
EC4	141 - 149	-33325	-463	-18783	-15154
EC5	150 - 159	-25362	-1342	-17736	-14616
EC1	160 - 166	-33889	-984	-19721	-16859
EC6	167 - 174	-36057	-3331	-20221	-16702

Table 6.2: Differential Forces

Difference in axial forces in first trial run at shape through the fourth for x, y, and z free to translate.

Cables	Members	1st Trial Run		2nd Trial Run		3rd Trial Run		4th Trial Run	
		max	min	max	min	max	min	max	min
RC2	1-7	-8133	-3462	-6911	-3946	-6928	-4591	-6930	-4592
RC3	8 - 17	-6109	-1022	-6868	-2159	-7108	-2424	-7111	-2426
RC4	18 - 28	-28486	-16402	-23825	-15394	-24277	-15853	-24273	-15861
RC5	29 - 36	-45244	-28307	-33768	-22897	-33629	-23568	-33632	-23572
RC6	37 - 73	-14009	-3171	-18624	-6484	-19725	-7109	-19715	-7095
RC1	44 - 57	-40810	-15948	-29257	-12299	-29834	-12286	-29834	-12286
RC7	58 - 64	-10583	-2507	-13218	-4900	-14494	-6037	-14495	-6039
RC8	65 - 70	-27200	-16476	-20513	-12073	-19804	-11654	-19801	-11681
RC9	71 - 77	-3272	-271	-3062	-327	-2991	-451	-2992	-451
RC10	78 - 85	-3156	-680	-2772	-63	-2503	-231	-2504	-233
EC7	86 - 91	-12331	-8276	-11719	-7474	-11999	-7662	-11987	-7662
EC8	92 - 97	-16114	-10907	-12401	-8078	-12284	-8002	-12285	-8006
EC9	98 - 108	-26017	-15093	-19697	-13121	-19236	-12849	-19236	-12850
EC2	109 - 128	-30169	-17068	-23488	-14797	-23214	-14944	-23214	-14944
EC3	129 - 140	-28984	-16945	-24013	-15239	-23682	-15148	-23684	-15149
EC4	141 - 149	-18793	-15155	-17740	-14074	-17842	-14205	-17843	-14205
EC5	150 - 159	-17737	-14616	-16010	-13339	-16086	-13458	-16087	-13457
EC1	160 - 166	-19722	-16859	-17481	-14928	-17917	-15269	-17918	-15272
EC6	167 - 174	-20221	-16702	-15563	-12469	-15602	-12414	-15601	-12416
Cable Net	(Initially 3000)	-6640	-2098	-4126	-1883	-3806	-2080	-3810	-2131

Table 6.3: Differential Forces per Trial Run

You can see the convergence of cables and the cable net.

Cables	Differnce from max and min from trial run to trial run (lbs)						Difference from max to min for each run (lb)			
	1st to 2nd		2nd to 3rd		3rd to 4th					
	max	min	max	min	max	min	1st	2nd	3rd	4th
RC2	1221	-484	-17	-645	-1	0	4670	2965	2337	2338
RC3	-759	-1137	-240	-268	-3	-2	5088	4709	4684	4685
RC4	4661	1008	-452	-458	3	-8	12084	8431	8424	8412
RC5	-11455	5710	139	-671	-3	-4	16916	10871	10061	10060
RC6	-4615	-3313	-1101	-625	10	14	10838	12140	12616	12620
RC1	10854	3649	123	13	0	1	24862	17657	17547	17548
RC7	2635	-2393	1276	-1137	-1	-2	8076	8318	8457	8457
RC8	6686	4403	710	419	3	-26	10723	8440	8149	7120
RC9	210	-56	71	-124	-1	0	3001	2735	2540	2541
RC10	384	617	269	-167	-1	-3	2176	1709	2272	2271
EC7	612	802	-280	-188	12	0	4054	4245	4337	4325
EC8	3713	2830	117	75	0	-4	5207	4323	4282	4279
EC9	6320	1972	460	272	0	-1	10923	655	6387	6386
EC2	3381	2271	274	-147	0	0	13101	8691	8270	8270
EC3	4972	1705	331	91	-2	-1	12040	8773	8533	8235
EC4	1044	1080	-103	-131	-1	0	3629	3665	3637	3638
EC5	1727	1277	-76	-119	-2	1	3121	2671	2627	2630
EC1	2240	1931	-435	-341	-2	-3	2819	2553	2648	2547
EC6	4659	4233	-39	55	1	-2	3519	3093	3187	3185

Table 6.4: Cable Diameter Sizing after Shapefinding

The maximum force along each cable is used to tabulate the required diameter as per the AISI Manual (Table 6).

Cables	Force (lb)	Diameter (per Table 6)	Area (per Table 6)
EC1	-17917	9/16	0.190
EC2	-23213	5/8	0.234
EC3	-23681	11/16	0.284
EC4	-17842	9/16	0.190
EC5	-16085	9/16	0.190
EC6	-17300	9/16	0.190
EC7	-9979	1/2	0.150
EC8	-12056	1/2	0.150
EC9	-19236	5/8	0.234
RC1	-29833	3/4	0.338
RC2	-6928	1/2	0.150
RC3	-1708	1/2	0.150
RC4	-24276	11/16	0.284
RC5	-33629	13/16	0.396
RC6	-23568	5/8	0.234
RC7	-17049	9/16	0.190
RC8	-19803	11/16	0.284
RC9	-11654	1/2	0.150
RC10	-2503	1/2	0.150

These areas will be used for the loaded run and the size will be bumped up as required for the worst load case.

Table 6.5: Cable Diameter Sizing after Loading

The maximum force along each cable is used to tabulate the required diameter as per the AISI Manual (Table 6).

Cables	Force (lb)	Diameter (per Table 6)	New Area (per Table 6)
EC1	-23801	11/16	0.284
EC2	-22203	5/8	0.234
EC3	-28131	3/4	0.338
EC4	-35022	13/16	0.396
EC5	-24647	11/16	0.284
EC6	-37353	13/16	0.396
EC7	-24806	11/16	0.284
EC8	-36170	13/16	0.396
EC9	-20421	5/8	0.234
RC1	-29874	3/4	0.338
RC2	-15833	9/16	0.190
RC3	-22426	11/16	0.284
RC4	-29996	3/4	0.338
RC5	-31109	3/4	0.338
RC6	-30144	3/4	0.338
RC7	-24174	5/8	0.234
RC8	-27542	3/4	0.338
RC9	-39856	7/8	0.459
RC10	-28200	3/4	0.338
Cable Net Max	-3810		
Min	-2132		

These diameters will be used to choose sockets from Appendix D. And detailing of the connection plate.

Table 6.6: AISI Cable Sizing Table

Properties of Zinc-Coated Steel Structural Strand

Nominal Diam. in	Minimum Breaking Strength in Tons of 2000 lbs. Class A Coating Throughout	Class A Coatin Inner Wires. Class B Outer Wires	Class A Coating Inner Wires Class C Outer Wires	Approx Gross Metallic Area. in2	Approx Weight, lb/ft
1/2	15.0	14.5	14.2	0.150	0.52
9/16	19.0	18.4	18	0.190	0.66
5/8	24.0	23.3	22.8	0.234	0.82
11/16	29.0	28.1	27.5	0.280	0.99
3/4	34.0	33.0	32.3	0.338	1.18
13/16	40.0	38.8	38	0.396	1.39
7/8	46.0	44.6	43.7	0.459	1.61
15/16	54.0	52.4	51.3	0.527	1.85
1	61.0	59.2	57.9	0.600	2.10
1 1/16	69.0	66.9	65.5	0.677	2.37
1 1/8	78.0	75.7	74.1	0.759	2.66
1 3/16	86.0	83.4	81.7	0.846	2.96
1 1/4	96.0	94.1	92.2	0.938	3.28
1 5/16	106.0	104.0	102	1.03	3.62
1 3/8	116.0	114.0	111	1.13	3.97
1 7/16	126.0	123.0	121	1.24	4.34
1 1/2	138.0	135.0	132	1.35	4.73
1 9/16	150.0	147.0	144	1.47	5.13
1 5/8	162.0	159.0	155	1.59	5.55
1 11/16	176.0	172.0	169	1.74	5.98
1 3/4	188.0	184.0	180	1.84	6.43
1 13/16	202.0	198.0	194	1.97	6.90
1 7/8	216.0	212.0	207	2.11	7.39
1 15/16	230.0	226.0	221	2.25	7.89
2	245.0	241.0	238	2.40	8.40
2 1/16	261.0	257.0	253	2.55	8.94
2 1/8	277.0	273.0	269	2.71	9.49
2 3/16	293.0	289.0	284	2.87	10.05
2 1/4	310.0	305.0	301	3.04	10.64
2 5/16	327.0	322.0	317	3.21	11.24
2 3/8	344.0	339.0	334	3.38	11.85
2 7/16	360.0	355.0	349	3.57	12.48
2 1/2	376.0	370.0	365	3.75	13.13
2 9/16	392.0	386.0	380	3.94	13.80
2 5/8	417.0	411.0	404	4.13	14.47
2 11/16	432.0	425.0	419	4.33	15.16
2 3/4	452.0	445.0	438	4.54	15.88
2 7/8	494.0	486.0	479	4.96	17.36
3	538.0	530.0	522	5.40	18.90
3 1/8	584.0	575.0	566	5.86	20.51
3 1/4	625.0	616.0	606	6.34	22.18
3 3/8	673.0	663.0	653	6.83	23.92
3 1/2	724.0	714.0	702	7.35	25.73
3 5/8	768.0	757.0	745	7.88	27.60
3 3/4	822.0	810.0	797	8.43	29.50
3 7/8	878.0	865.0	852	9.00	31.50
4	925.0	911.0	897	9.60	33.60

CHAPTER 7

DATA

1st Run with loads.

Mem.	Original Prestress	Shape	20psf Down	Up
1	-6928	-6953	-25839	-7541
2	-6776	-7009	-12408	-3658
3	-5732	-5995	-11970	-7728
4	-5145	-5357	-11199	-9875
5	-4865	-5027	-8269	-3985
6	-4930	-5202	-22434	-22567
7	-4591	-4977	-5293	-13379
8	-7108	-6552	-13955	-1357
9	-5749	-5947	-9704	-2993
10	-5664	-5690	-6162	-6902
11	-4713	-4798	-20196	-16638
12	-4031	-3946	-4439	-8817
13	-3925	-3908	-5406	-6014
14	-3252	-3131	-10029	-12750
15	-2714	-2561	-11497	-11018
16	-2682	-2416	-10807	-11334
17	-2424	-1656	-21867	-16227
18	-24277	-22700	-26481	-20217
19	-22518	-21227	-21122	-22525
20	-22415	-21513	-24425	-19755
21	-20901	-20126	-23237	-19937
22	-19628	-18892	-17454	-20827
23	-19597	-19054	-13186	-26127
24	-18599	-18003	-11866	-28340
25	-17663	-17265	-9776	-26607
26	-17708	-17164	-10281	-24766
27	-16778	-15970	-10469	-23223
28	-15853	-13412	-12026	-17662
29	-33629	-31352	-35167	-29007
30	-32075	-30431	-30713	-30751
31	-30803	-29672	-28767	-31186
32	-29639	-28544	-25844	-31568
33	-28481	-27230	-23266	-31701
34	-27278	-25665	-21923	-31163
35	-25786	-23386	-22914	-334[illegible]
36	-23569	-19138	-28982	-28424
37	-19725	-17733	-24990	-12080
38	-16433	-15594	-17509	-14555
39	-14028	-13483	-12403	-16483
40	-11970	-11462	-9179	-14481
41	-9910	-9108	-10160	-14126
42	-8165	-6758	-7876	-12165
43	-7109	-3560	-24099	-23846
44	-29834	-28938	-38147	-24307
45	-25903	-26141	-29260	-24468
46	-22717	-23041	-21933	-25099
47	-20115	-20290	-21461	-20303
48	-17990	-18229	-18807	-18594

49	-16224	-16482	-13463	-20671	
50	-14759	-15012	-10071	-24287	
51	-13581	-13817	-5445	-24042	
52	-12734	-12807	-7102	-23004	
53	-12287	-12069	-7164	-19318	
54	-12332	-11958	-7358	-17188	
55	-12982	-12739	-9664	-17329	
56	-14470	-14292	-12361	-17714	
57	-17050	-16133	-12780	-32131	
58	-14494	-13859	-24554	-5794	
59	-11884	-11707	-18024	-6880	
60	-10092	-9880	-13172	-7377	
61	-8573	-8162	-9129	-11696	
62	-7259	-6395	-7501	-15247	
63	-6331	-5220	-5830	-8886	
64	-6037	-4893	-24988	-21469	
65	-19804	-19366	-18482	-21337	
66	-17477	-17040	-11874	-22809	
67	-15735	-15413	-12667	-19735	
68	-14239	-13972	-12027	-16681	
69	-12752	-12314	-14339	-17410	
70	-11655	-10628	-26112	-28867	
71	-2991	-3413	-10596	0	Member in compression
72	-1875	-2216	-6362	0	Member in compression
73	-1242	-1355	-6992	-3759	
74	-868	-986	-10903	-13488	
75	-577	-610	-12899	-12764	
76	-451	-431	-2282	-7163	
77	-489	-413	-5920	-12015	
78	-2503	-2996	-24299	-6733	
79	-1885	-1764	-2734	-1831	
80	-1086	-1704	-6397	-4114	
81	-801	-1219	-2371	-4068	
82	-509	-780	-6475	-3435	
83	-378	-734	-5453	0	Member in compression
84	-298	-1199	-5457	0	Member in compression
85	-231	-1090	-14779	-19056	
86	-7662	-7021	-15670	-14386	
87	-8322	-7929	-10017	-12471	
88	-9980	-9791	-10012	-12466	
89	-8461	-8456	-14214	-13976	
90	-8007	-7835	-11119	-13042	
91	-11999	-10879	-16801	-9720	
92	-8003	-6806	-16352	0	Member in compression
93	-10720	-10328	-20620	-11728	
94	-10212	-10006	-19864	-13489	
95	-10703	-10561	-15184	-12552	
96	-12056	-11731	-18087	-13815	
97	-12284	-10182	-22414	-16897	
98	-19236	-16104	-12605	-18409	
99	-17241	-15484	-12439	-18960	

1 run

100	-15923	-14759	-18265	-23025
101	-12849	-11978	-17868	-24921
102	-13820	-13267	-18868	-27897
103	-15448	-15082	-17459	-24208
104	-14036	-12845	-19349	-28502
105	-16325	-15663	-27766	-29605
106	-16053	-14910	-17263	-17033
107	-18886	-17331	-18514	-19137
108	-18817	-15813	-16987	-18255
109	-22361	-20223	-23091	-26013
110	-19593	-19318	-21329	-19387
111	-20163	-20551	-23674	-18879
112	-17702	-18129	-21140	-20747
113	-18926	-19191	-21473	-23478
114	-16807	-16792	-14679	-20074
115	-14944	-14545	-11918	-23348
116	-17597	-17396	-20559	-21836
117	-16824	-16535	-20618	-19429
118	-16819	-16433	-23105	-18181
119	-17546	-17362	-22220	-13447
120	-18840	-18772	-24354	-19476
121	-20545	-20565	-23087	-19583
122	-17958	-17737	-17773	-19934
123	-20195	-20193	-20951	-25226
124	-22484	-22956	-24026	-24271
125	-20744	-21507	-25265	-24083
126	-23214	-23581	-30326	-26505
127	-21541	-21783	-27580	-24567
128	-22608	-21788	-30223	-29938
129	-23682	-22154	-20559	-22207
130	-22701	-21832	-23598	-21484
131	-21840	-21168	-29059	-21069
132	-18939	-18250	-19268	-18571
133	-18581	-18112	-24072	-25399
134	-18610	-18272	-20253	-24928
135	-16193	-14947	-6922	-26925
136	-17055	-16803	-18811	-19287
137	-15148	-14711	-18489	-13146
138	-17279	-16931	-19571	-17949
139	-16377	-15897	-19976	-17666
140	-16110	-15111	-16271	-13424
141	-16697	-17888	-17181	-24768
142	-17843	-18159	-18116	-20030
143	-15557	-16526	-15114	-20049
144	-17359	-17729	-23126	-24839
145	-15696	-16039	-11355	-25292
146	-14565	-14590	-11411	-19079
147	-14206	-14253	-14134	-17465
148	-14489	-14582	-13664	-17845
149	-15313	-15289	-15250	-20238
150	-16086	-16023	-17957	-21852

151	-13505	-13288	-15764	-16887
152	-15546	-15470	-17517	-18377
153	-13458	-13288	-15476	-13185
154	-15942	-15849	-15888	-16788
155	-14521	-14379	-13869	-16218
156	-13661	-13538	-13547	-19006
157	-13525	-13601	-9697	-19226
158	-14117	-14599	-13451	-25301
159	-15251	-15998	-18370	-28043
160	-17917	-18032	-25499	-28001
161	-16641	-16599	-21382	-22141
162	-15736	-15658	-17775	-15162
163	-15269	-15287	-19063	-13353
164	-15334	-15324	-18199	-15131
165	-16044	-16049	-18307	-18261
166	-17301	-17338	-37913	-36450
167	-15602	-15798	-22798	-28132
168	-14313	-14208	-16966	-21424
169	-13673	-13418	-15213	-17419
170	-13859	-13563	-21627	-22691
171	-14839	-14589	-17214	-14679
172	-12414	-11822	-21288	-6213
173	-14303	-13950	-21532	-13206
174	-14618	-14072	-18594	-12273

Since there are members in compression, so I will have to raise the prestress of those cables.

2nd Run with loads.

Mem.	Original Prestress	Shape	20psf Down	Up
1	-6948	-6969	-23600	-7355
2	-6794	-7050	-11831	-4119
3	-5750	-6010	-11403	-7695
4	-5163	-5369	-11671	-10564
5	-4883	-5041	-7888	-3989
6	-4947	-5215	-23801	-23664
7	-4609	-4950	-4251	-12943
8	-7104	-6559	-13246	-1877
9	-5744	-5916	-9257	-3439
10	-5660	-5660	-5853	-6944
11	-4709	-4795	-19876	-16452
12	-4026	-3959	-4518	-8721
13	-3921	-3913	-5445	-6095
14	-3248	-3142	-10447	-13004
15	-2711	-2583	-11356	-10989
16	-2680	-2448	-10598	-11119
17	-2422	-1746	-22203	-16895
18	-24342	-22842	-26339	-20584
19	-22583	-21371	-21316	-22508
20	-22477	-21593	-24678	-19640
21	-20961	-20220	-23326	-20145
22	-19682	-18975	-17619	-20808
23	-19634	-19113	-13381	-25995
24	-18623	-18049	-12109	-28131
25	-17668	-17296	-9947	-26449
26	-17669	-17157	-10354	-24626
27	-16707	-15948	-10375	-23203
28	-15751	-13407	-11522	-18151
29	-33660	-31519	-35022	-29390
30	-32106	-30572	-30853	-30829
31	-30831	-29772	-28872	-31221
32	-29660	-28634	-26011	-31560
33	-28490	-27312	-23467	-31656
34	-27269	-25743	-21979	-31041
35	-25753	-23476	-23195	-33440
36	-23496	-19243	-28041	-28306
37	-19752	-17857	-24398	-12851
38	-16460	-15649	-17157	-14779
39	-14053	-13538	-12538	-16503
40	-11993	-11510	-9369	-14573
41	-9930	-9160	-10537	-14494
42	-8184	-6815	-7640	-12360
43	-7127	-3615	-23692	-24647
44	-29738	-28946	-37353	-24722
45	-25805	-26089	-28923	-24597
46	-22618	-22982	-21993	-24889
47	-20015	-20222	-21230	-20149
48	-17890	-18193	-18892	-18338

Maximum force on cablenet
-3810.32 LB

Minimum force on cablenet
-2131.46 LB

49	-16123	-16443	-13629	-20220
50	-14657	-14906	-9406	-23908
51	-13477	-13654	-5403	-24533
52	-12627	-12601	-5493	-22531
53	-12177	-11922	-6802	-18753
54	-12217	-11920	-8498	-16307
55	-12855	-12760	-11369	-16314
56	-14319	-14439	-13474	-16894
57	-16861	-17759	-20716	-27789
58	-14530	-14258	-24806	-5706
59	-11961	-11902	-18050	-7431
60	-10186	-10052	-12943	-7674
61	-8673	-8411	-8918	-11630
62	-7359	-6852	-7912	-14939
63	-6429	-5876	-5941	-8909
64	-6135	-5759	-23994	-21323
65	-19270	-18954	-18060	-20607
66	-16994	-16603	-11661	-22166
67	-15274	-15020	-12316	-19701
68	-13786	-13595	-11910	-17217
69	-12300	-12035	-12718	-17549
70	-11194	-10602	-31423	-36170
71	-5041	-5510	-12194	-207
72	-4026	-4345	-8348	-1605
73	-3549	-3651	-10026	-7099
74	-3232	-3248	-8753	-10477
75	-3152	-3127	-17834	-20421
76	-3209	-3114	-3142	-6536
77	-3711	-3428	-11855	-14784
78	-3530	-3277	-29874	-16095
79	-3050	-2706	-4892	-2457
80	-2383	-2294	-11434	-8887
81	-2198	-2232	-5651	-10518
82	-1972	-2214	-6341	-6034
83	-1889	-2187	-3843	-956
84	-1826	-2426	-3734	-2185
85	-1836	-2666	-14061	-17948
86	-7676	-7083	-15772	-14675
87	-8336	7959	-9839	-12280
88	-9993	-9830	-9982	-12422
89	-8471	-8483	-14067	-14012
90	-8012	-7866	-10856	-13236
91	-12003	-10952	-15833	-10607
92	-9337	-7177	-16348	-339
93	-11068	-10705	-20962	-12354
94	-10566	-10365	-19963	-13776
95	-11067	-10922	-15438	-12810
96	-12424	-12112	-18325	-14118
97	-12619	-10598	-22426	-17226
98	-19255	-16256	-12765	-18722
99	-17252	-15577	-12410	-19088

2 run

100	-15935	-14824	-18115	-23041
101	-12863	-12023	-17443	-24611
102	-13834	-13298	-18402	-27384
103	-15462	-15108	-18315	-24676
104	-14049	-12919	-20042	-28714
105	-16339	-15718	-28228	-29996
106	-16066	-14991	-17021	-16931
107	-18899	-17419	-18529	-19548
108	-18830	-15894	-16009	-18973
109	-22371	-20212	-21961	-27057
110	-19603	-19287	-20418	-19867
111	-20175	-20489	-22913	-19511
112	-17715	-18059	-20173	-20955
113	-18940	-19149	-20454	-23489
114	-16822	-16774	-14761	-20545
115	-14961	-14594	-12744	-23584
116	-17617	-17423	-20742	-21964
117	-16846	-16581	-20403	-19455
118	-16843	-16508	-23278	-18502
119	-17572	-17478	-22451	-13399
120	-18872	-18877	-24182	-18971
121	-20584	-20642	-22711	-19489
122	-18000	-17827	-18766	-20133
123	-20250	-20278	-21624	-24916
124	-22550	-22996	-23876	-24146
125	-20812	-21507	-25298	-23986
126	-23286	-23706	-30273	-26389
127	-21610	-22022	-27800	-24363
128	-22672	-22657	-31109	-29707
129	-23756	-23117	-22318	-22618
130	-22774	-22271	-24079	-22003
131	-21912	-21408	-28666	-21939
132	-19010	-18443	-18947	-19272
133	-18649	-18295	-24008	-25539
134	-18673	-18414	-20148	-25038
135	-16241	-15406	-4215	-30144
136	-17095	-16950	-18731	-19690
137	-15179	-14932	-18118	-13414
138	-17300	-17106	-18822	-17930
139	-16395	-16128	-18572	-17424
140	-16125	-15554	-15834	-15739
141	-16898	-17595	-16572	-21844
142	-18032	-18244	-18425	-19444
143	-15756	-16372	-17280	-17901
144	-17553	-17754	-23137	-24151
145	-15851	-15942	-10401	-24174
146	-14655	-14524	-12390	-18684
147	-14193	-14082	-17089	-17629
148	-14338	-14220	-13824	-15812
149	-15000	-14806	-15585	-18353
150	-15217	-15028	-17482	-19058

2 run

151	-12824	-12773	-15890	-14151	
152	-14921	-14866	-17383	-15413	
153	-12981	-12931	-18336	-10721	
154	-15580	-15541	-17011	-15926	
155	-14241	-14189	-15547	-15630	
156	-13433	-13397	-15325	-18475	
157	-13319	-13415	-11875	-17090	
158	-13878	-14293	-16987	-24098	
159	-14972	-15661	-20369	-27542	
160	-17917	-18099	-25120	-26586	
161	-16631	-16670	-21488	-21315	
162	-15717	-15737	-18475	-14974	
163	-15244	-15317	-18259	-13375	
164	-15305	-15380	-17822	-15581	
165	-16013	-16119	-19333	-19316	
166	-17269	-17400	-39856	-37975	
167	-15605	-15729	-22465	-28200	
168	-14317	-14166	-16684	-21481	
169	-13675	-13436	-15365	-17477	
170	-13861	-13604	-21702	-22665	
171	-14840	-14631	-17101	-14664	
172	-12414	-11916	-21086	-6562	
173	-14303	-14012	-21469	-13459	
174	-14616	-14138	-18492	-12694	
CableNet	-3808	-3808	-3807	-3810	Max
	-2082	-2082	-2132	-2131	Min

There are no members in compression in all three load conditions.

CHAPTER 8

CONNECTION PLATE SIZING CALCULATIONS

Connection Input Data

>	2	Cable Work Point
>	EC-1	Cable (Name) Designation
>	7 / 8 "	Cable Diameter
>	39.86 kips	Cable Force
>	strand	Cable Type
>	open spelter	Fitting Type (Choices are: Open Spelter, Open Swage, or Jaw)
>	0.000 in	**Plate Thickness Override**
>	36.0 ksi	Steel Yeild Strength of Connection Material
>	1/4 "	Clearance Between Boss plates & Fitting
>	1/4 "	Clearance for Conn. Plate Radius
>	7	Net Width of Plate to Thickness Ratio (value range 6 to 8)

Design is >> OK

Cable and Fitting Geometry

0.875 in	Specified Strand Size
43.7 k	Minimum Cable Capacity class A/C coating
2.000 in	Pin Diamter of Fitting
2.000 in	Width at Pin
3.750 in	Max. Radius for Connection Plate
6.000 in	Diamter of Boss Plate
43.7 k	Fitting Capacity

Allowable Stresses (ksi)

36.0 ksi	Yeild Strength of Connection Material
16.2 ksi	Allowable Tensile Stress (Ft=0.45 Fy)
32.4 ksi	Allowable Bearing Stress (Fp=0.9 Fy)
21.6 ksi	Allowable Bending Stress (Fb=0.6*Q*Fy) (if applicable)

Plate Thickness Based on Bearing

t plate = Cable Force / (Fp * pin ø) = 39.86 kips / (32.4 ksi * 2.000 in) = 0.615 in say ***0.625 in*** ***5/8 "***

Plate Width Based on Tension and Thickness determined above

plate width = Cable Force / (Ft * t plate) = 39.86 kips / (16.2 ksi * 0.625 in) = 3.937 in say ***4.000 in*** ***4 "***

Other Required Minimum Plate Geometry

min. side =	3 * min. plate t	=	3 *	0.615 in	=	1.845 in
max. side =	4 * min plate t	=	4 *	0.615 in	=	2.460 in
min. front =	1.333 * min. side	=	1.333 *	1.845 in	=	2.460 in
max. front =	1.333 * max. side	=	1.333 *	2.460 in	=	3.280 in

Plate Geometry Provided

Governing Plate Thickness	=	***0.625 in***	***5/8 "***					
Plate Width at Pin Hole	=	***7.625 in***	***8 "***					
Max. Radius for Connection Plate	=	3.750 in		>	1.845 in	=	(min. side)	OK
Max. Radius for Connection Plate	=	3.750 in		>	2.460 in	=	(min. front)	OK

Check Actual Stresses on Connection Plate

f p = Cable Force / (pin ø * t plate) = 39.86 kips / (2.000 in * 0.625 in) = 31.89 ksi < Fp = 32.4 ksi OK

f t = Cable Force / (w plate * t plate) = 39.86 kips / (4.000 in * 0.625 in) = 15.94 ksi < Ft = 16.2 ksi OK

Longitudinal Weld Requirement

Cable Force =	39.9 k	Min. Weld =	0.3125 in	=	5/16 "
Conn. Plate =	0.625 in	Weld Cap. =	4.64 kips	per inch	

Plate Size Results

Plate Size =	*5/8 "*	t x	*8 "*	w & Pl Radius =	*3 3/4 "*
Boss Plate Size =	*9/16 "*	t x	*6 "*	ø each side	

Boss Plate To End Fitting Clearance on each side 0.25 in

Weld Length =	*9.0 in*	*or 2 @*	*5.0 in*	*of*	*5/16 "*	***Fillet Weld***
		or 4 @	*3.0 in*	*of*	*5/16 "*	***Fillet Weld***

Master's Thesis by Jairo Rios

Connection Plate Sizing Calculation

Connection Input Data

>	2	Cable Work Point
>	EC-6	Cable (Name) Designation
>	3/4 "	Cable Diameter
>	28.20 kips	Cable Force
>	strand	Cable Type
>	open spelter	Fitting Type (Choices are: Open Spelter, Open Swage, or Jaw)
>	0.000 in	**Plate Thickness Override**
>	36.0 ksi	Steel Yeild Strength of Connection Material
>	1/4 "	Clearance Between Boss plates & Fitting
>	1/4 "	Clearance for Conn. Plate Radius
>	7	Net Width of Plate to Thickness Ratio (value range 6 to 8)

Design is >> ***OK***

Cable and Fitting Geometry

0.750 in	Specified Strand Size
32.3 k	Minimum Cable Capacity class A/C coating
1.630 in	Pin Diamter of Fitting
1.750 in	Width at Pin
3.250 in	Max. Radius for Connection Plate
5.000 in	Diamter of Boss Plate
32.3 k	Fitting Capacity

Allowable Stresses (ksi)

36.0 ksi	Yeild Strength of Connection Material
16.2 ksi	Allowable Tensile Stress (Ft=0.45 Fy)
32.4 ksi	Allowable Bearing Stress (Fp=0.9 Fy)
21.6 ksi	Allowable Bending Stress (Fb=0.6*Q*Fy) (if applicable)

Plate Thickness Based on Bearing

t plate = Cable Force / (Fp * pin ø) = 28.20 kips / (32.4 ksi * 1.630 in) = 0.534 in say ***0.563 in*** ***9/16 "***

Plate Width Based on Tension and Thickness determined above

plate width = Cable Force / (Ft * t plate) = 28.20 kips / (16.2 ksi * 0.563 in) = 3.095 in say ***3.250 in*** ***3 1/4 "***

Other Required Minimum Plate Geometry

min. side =	3 * min. plate t	=	3 *	0.534 in	=	1.602 in
max. side =	4 * min plate t	=	4 *	0.534 in	=	2.136 in
min. front =	1.333 * min. side	=	1.333 *	1.602 in	=	2.135 in
max. front =	1.333 * max. side	=	1.333 *	2.136 in	=	2.847 in

Plate Geometry Provided

Governing Plate Thickness	=	***0.563 in***	***9/16 "***					
Plate Width at Pin Hole	=	***6.625 in***	***6 3/4 "***					
Max. Radius for Connection Plate	=	3.250 in		>	1.602 in	=	(min. side)	***OK***
Max. Radius for Connection Plate	=	3.250 in		>	2.135 in	=	(min. front)	***OK***

Check Actual Stresses on Connection Plate

f p = Cable Force / (pin ø * t plate) = 28.20 kips / (1.630 in * 0.563 in) = 30.76 ksi < Fp = 32.4 ksi ***OK***

f t = Cable Force / (w plate * t plate) = 28.20 kips / (3.250 in * 0.563 in) = 15.43 ksi < Ft = 16.2 ksi ***OK***

Longitudinal Weld Requirement

Cable Force =	28.2 k	Min. Weld =	0.3125 in	=	***5/16 "***
Conn. Plate =	0.563 in	Weld Cap. =	4.64 kips	per inch	

Plate Size Results

Plate Size =	***9/16 "***	t x	***6 3/4 "***	w & Pl Radius =	***3 1/4 "***	
Boss Plate Size =	***7/16 "***	t x	***5 "***	ø each side		

Boss Plate To End Fitting Clearance on each side
0.31 in

Weld Length =	*7.0 in*	*or 2 @*	*4.0 in*	*of*	***5/16 "***	***Fillet Weld***
		or 4 @	*2.0 in*	*of*	***5/16 "***	***Fillet Weld***

Master's Thesis by Jairo Rios

Connection Plate Sizing Calculation

Connection Input Data

>	2	*Cable Work Point*
>	RC-2	*Cable (Name) Designation*
>	11/16"	*Cable Diameter*
>	23.80 kips	*Cable Force*
>	strand	*Cable Type*
>	open spelter	*Fitting Type (Choices are: Open Spelter, Open Swage, or Jaw)*
>	0.000 in	***Plate Thickness Override***
>	36.0 ksi	*Steel Yeild Strength of Connection Material*
>	1/4 "	*Clearance Between Boss plates & Fitting*
>	1/4 "	*Clearance for Conn. Plate Radius*
>	7	*Net Width of Plate to Thickness Ratio (value range 6 to 8)*

Design is >> ***OK***

Cable and Fitting Geometry

0.688 in	*Specified Strand Size*
27.5 k	*Minimum Cable Capacity class A/C coating*
1.630 in	*Pin Diamter of Fitting*
1.750 in	*Width at Pin*
3.250 in	*Max. Radius for Connection Plate*
5.000 in	*Diamter of Boss Plate*
27.5 k	*Fitting Capacity*

Allowable Stresses (ksi)

36.0 ksi	*Yeild Strength of Connection Material*
16.2 ksi	*Allowable Tensile Stress (Ft=0.45 Fy)*
32.4 ksi	*Allowable Bearing Stress (Fp=0.9 Fy)*
21.6 ksi	*Allowable Bending Stress (Fb=0.6*Q*Fy)*
	(if applicable)

Plate Thickness Based on Bearing

$$t\ plate = \frac{\text{Cable Force}}{(\text{Fp} * \text{pin } \varnothing)} = \frac{23.80\ \text{kips}}{32.4\ \text{ksi} * 1.630\ \text{in}} = 0.451\ \text{in}$$

say ***0.500 in*** ***1/2 "***

Plate Width Based on Tension and Thickness determined above

$$\text{plate width} = \frac{\text{Cable Force}}{(\text{Ft} * \text{t plate})} = \frac{23.80\ \text{kips}}{16.2\ \text{ksi} * 0.500\ \text{in}} = 2.938\ \text{in}$$

say ***3.000 in*** ***3 "***

Other Required Minimum Plate Geometry

min. side =	*3 * min. plate t*	=	*3 **	*0.451 in*	=	*1.352 in*
max. side =	*4 * min plate t*	=	*4 **	*0.451 in*	=	*1.803 in*
min. front =	*1.333 * min. side*	=	*1.333 **	*1.352 in*	=	*1.802 in*
max. front =	*1.333 * max. side*	=	*1.333 **	*1.803 in*	=	*2.403 in*

Plate Geometry Provided

Governing Plate Thickness	=	***0.500 in***	***1/2 "***					
Plate Width at Pin Hole	=	***6.625 in***	***6 3/4 "***					
Max. Radius for Connection Plate	=	*3.250 in*		>	*1.352 in*	=	(min. side)	***OK***
Max. Radius for Connection Plate	=	*3.250 in*		>	*1.802 in*	=	(min. front)	***OK***

Check Actual Stresses on Connection Plate

$$f\,p = \frac{\text{Cable Force}}{(\text{pin } \varnothing * \text{t plate})} = \frac{23.80\ \text{kips}}{1.630\ \text{in} * 0.500\ \text{in}} = 29.20\ \text{ksi} < \text{Fp} = 32.4\ \text{ksi}$$ ***OK***

$$f\,t = \frac{\text{Cable Force}}{(\text{w plate} * \text{t plate})} = \frac{23.80\ \text{kips}}{3.000\ \text{in} * 0.500\ \text{in}} = 15.87\ \text{ksi} < \text{Ft} = 16.2\ \text{ksi}$$ ***OK***

Longitudinal Weld Requirement

Cable Force =	*23.8 k*	Min. Weld =	*0.3125 in*	=	***5/16 "***
Conn. Plate =	*0.500 in*	Weld Cap. =	*4.64 kips*	*per inch*	

Plate Size Results

Plate Size =	***1/2 "***	t x	***6 3/4 "***	w & Pl Radius =	***3 1/4 "***	
Boss Plate Size =	***1/2 "***	t x	***5 "***	ø each side		

Boss Plate To End Fitting
Clearance on each side
0.25 in

Weld Length =	*6.0 in*	*or 2 @*	*4.0 in*	*of*	***5/16 "***	***Fillet Weld***
		or 4 @	*2.0 in*	*of*	***5/16 "***	***Fillet Weld***

APPENDIX A

WHAT ARE FABRIC STRUCTURES?

Fabric structures may be divided into two categories: air supported and tensioned.

A.1 Air Supported Structures

General

Air supported structures are, as their name states, held up by air pressure. The inside of the structures is pressurized like a balloon. While this might seem at first to be uncomfortable to the occupants of the structure, the pressure differential is no greater than that of ordinary barometric fluctuations. Common uses of air supported structures include sports stadiums, the "bubbles" used to cover tennis courts and pools, and many other temporary shelters.

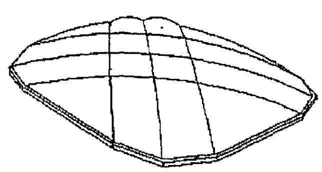


Figure A.1: Air Supported Dome

Types

The two basic types of air supported structures are high profile and low profile. Profile refers to the height to the structure relative to its span. High profile structures are typically used for temporary or storage facilities and are often free standing, which means they have no foundation upon which they rest. Low profile structures are used to span long distances such as sports stadiums, also low profile structures tend to be placed upon a building rather then the ground itself, thus being used as roofs. This is due to the forces involved in supported the structure. High profile air supported structures are less common today because the cost of comparable tension fabric structures has been reduced considerable.

Here are some geometric plans for low profile air supported structures:

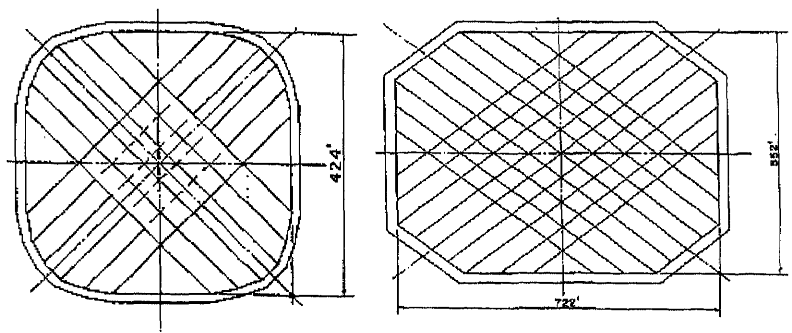
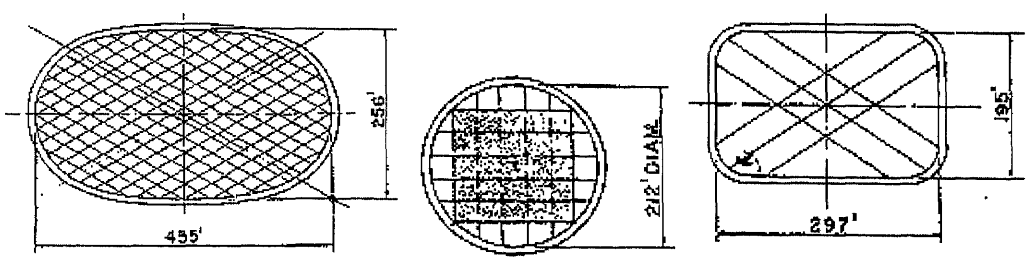


Figure A.2 – A.3: Ring Beam 1 and 2



Figures A.4 - A.6: Ring Beam 3, 4 and 5

The crosshatched lines are the cables that hold the roof down.

Advantages and Disadvantages

First costs for an air-supported roof always have compared favorably with those of conventional roof structures. On a cost-per-seat basis, the advantage is even more evident. The savings come from lower construction and supporting structure costs plus overall economy of design. Architecturally, the design is very elegant and dramatic.

Unintentional deflation and the cost associated with it are the major problem with these structures. The most common cause of deflation is accumulating snow and resulting ponding. The introduction of design refinements, such as computer patterning, and greater knowledge and planning on the part of operators has helped reduce the occurrences in the recent past.

Structural Principle

Air pressure is used to support and stabilize air-supported structures. When air is placed under pressure it exerts a uniform force in all directions. This force is used to support the fabric. The cables do not support the fabric, but hold it down. The fabric is attached to the cables in panels resulting in a hybrid membrane. The hybrid membrane transfers the stresses from the fabric to the cables. The cables are attached to a compression ring, which resists the uplifting forces.

Configurations

The most basic shape is a low profile oval with a diagonal cable pattern and a funicular compression ring. Funicular implies that there are no bending moments in the compression ring. A rectangular shape with modified corners and two-way cable systems will keep a compression ring funicular. One way cable systems in a modified rectangular structure produce moments in the compression ring. High profile air supported structures may use one or two way cable systems or just fabric alone. Consideration of fabric design and shipping will limit cable spacing to a maximum of 45 ft (14m). Due to fabrication and cost of connections, the minimum cable spacing considered economically feasible is 35 ft (11m) on center.

A.2 Tension Structures

The basic types of tension structures are cable domes, mast supported, arch supported, radial tent and saddle roofs. The distinction between roof and wall is indistinct. Tension structures can economically span large distances without internal obstructions without the need for any mechanical systems. Architecturally, these structures are more pleasing since there are many different and dynamic shapes that can be built. The main drawback of tension structures is that feasibly a computer must be used since the shape is governed by complex differential equations.

STRUCTURAL PRINCIPALS

Tension structures consists of cables and fabric in tension. The cables carry the gravity loads while stability and resistance to wind uplift is provided by the weight of the roof deck system. The most common type, the cable dome, consists of a center tension ring surrounded by a number of hoop rings, which are also in tension; these are surrounded at the perimeter by a compression ring.

SHAPES:

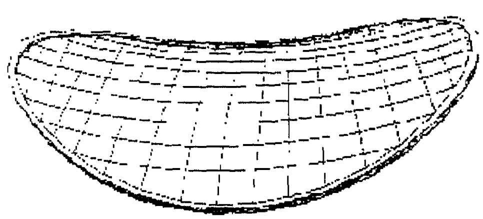


Figure A.7: Saddle Roof

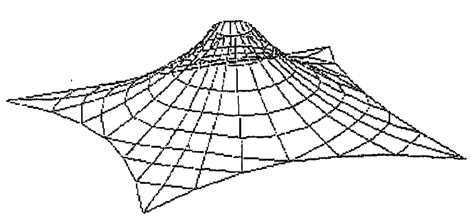


Figure A.8: Radial Tent

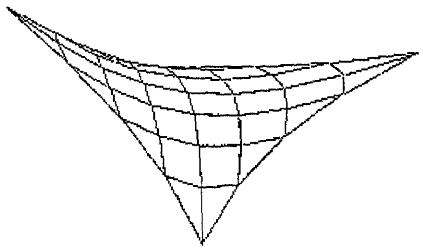
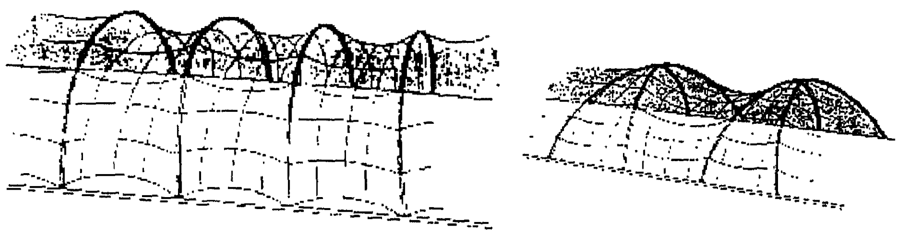
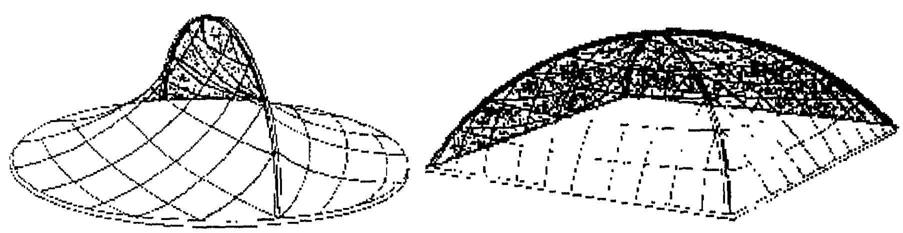


Figure A.9: Orthogonal Anticlastic Saddle

ARCH SUPPORTED MEMBRANE:

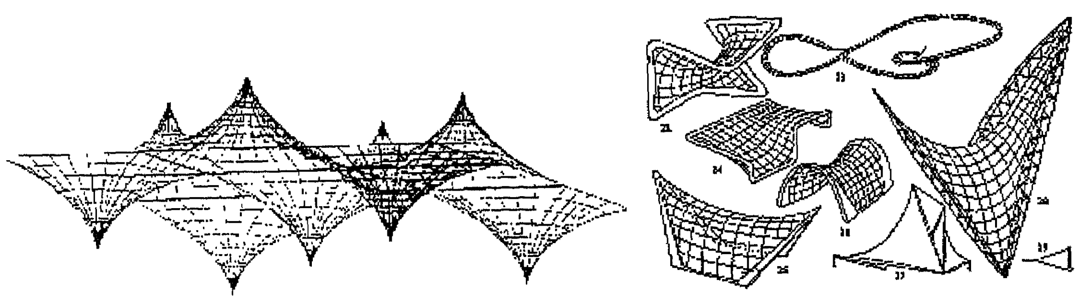


Figures A.10 – A.11: Arch 1 and 2



Figures A.12 – A.13: Arch 3 and 4

CONBINATIONS:



Figures A.14 – A.15: Combination 1 and 2

APPENDIX B

NONLINEAR ANALYSIS

The fabric can be modeled using cables, since they can only develop strength to resist normal forces using prestress. Linear Elastic theory approximates the length change of a bar by the dot product of the direction vector and the displacement.

$$\textit{Length Change} \sim \underline{\eta} \cdot \underline{\delta}$$

But you can see from the figures below, that they are perpendicular to each other therefore the dot product is zero. It is therefore necessary to use geometrically nonlinear analysis.

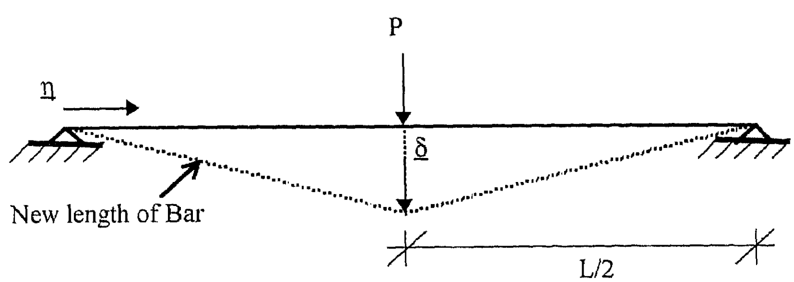


Figure B.1: Geometrically Nonlinear Structure

The geometry of the structure itself is unstable as opposed to a structure below.

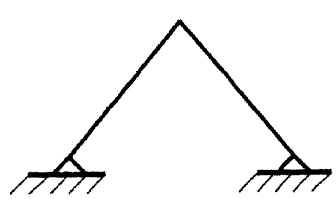
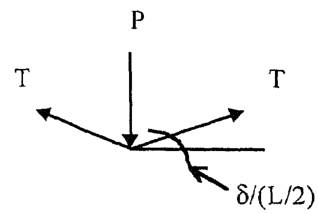


Figure B.2: Geometrically Stable Structure

The effects of prestress on the structure make it stronger. It is now able to counter the external forces.



The sum of the forces: $2T\cdot(2\delta/L) = P$

$P = (4T/L)\cdot\delta$

Figure B.3: Nodal Equilibrium

This is essentially the reason why fabric structures need to be analyzed using a geometrically nonlinear approach.

APPENDIX C

AISI STEEL CABLE MANUAL

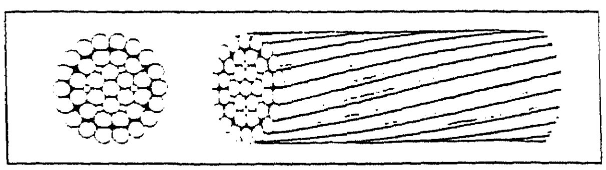
3—RELATIVE ADVANTAGES OF STRAND AND WIRE ROPE

Strand

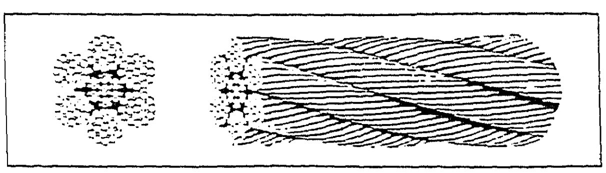
a. The carrying capacity of a strand is greater than that of a rope of the same diameter.
b. The outside surface of strand is smoother than that of wire rope. Therefore, it is easier to protect with paint or other covering.
c. Accessory fittings used with strands are smaller than those used with wire rope because the strand diameter required for a given load is smaller.
d. Strand has a higher modulus of elasticity than wire rope.

Wire Rope

a. Wire rope is easier to handle in the field because it is more flexible than strand.
b. A wire rope saddle is generally smaller than a strand saddle because wire rope can be bent to a shorter radius than strand.
c. Because wire rope is more flexible than strand, the angle change at bands and clamps can be larger.



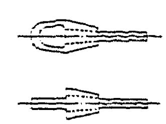
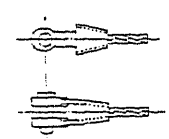
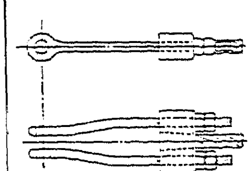
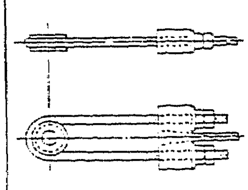
Strand



Wire Rope

4—STANDARD END FITTINGS

Standard End Fittings Developing the Breaking Strength of the Cable

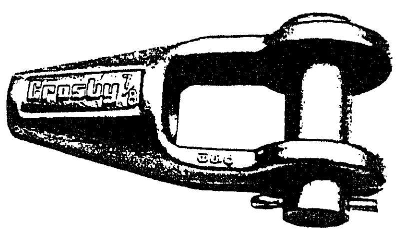
Name	Description	Attachment	Sizes Available Diam. in. Strand	Sizes Available Diam. in. Rope
Open Socket		Poured Zinc	½–4	⅜–4
Closed Socket		Poured Zinc	½–4	⅜–4
Open Bridge Socket		Poured Zinc	½–4	⅜–4
Closed Bridge Socket		Poured Zinc	½–4	⅜

APPENDIX D

CROSBY CABLE FITTING CATALOG

Spelter Sockets

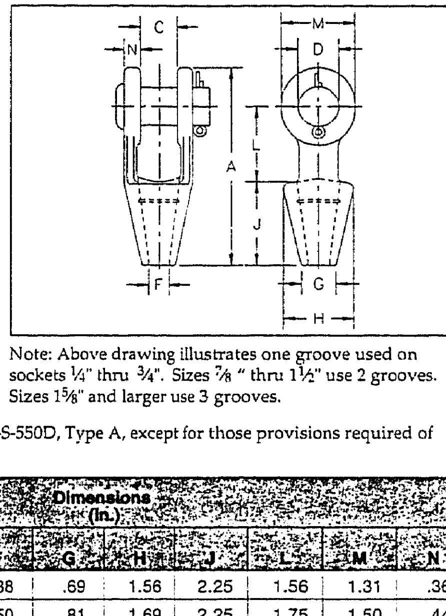
GROOVED OPEN SPELTER SOCKETS



G-416

- Forged Steel Sockets thru 1½", cast alloy steel 1-5/8" thru 4".
- Spelter socket terminations have an efficiency rating of 100%, based on the catalog strength of wire rope. Ratings are based on recommended use with 6 x 7, 6 x 19, or 6 x 37, IPS or XIP (EIP), XXIP (EEIP), RRL, FC, or IWRC wire rope.

NOTICE: All cast steel sockets 1⅝" and larger are magnetic particle inspected and ultrasonic inspected.Proof testing available on special order.



Note: Above drawing illustrates one groove used on sockets ¼" thru ¾". Sizes ⅞ " thru 1½" use 2 grooves. Sizes 1⅝" and larger use 3 grooves.

Open Grooved Sockets meet the performance requirements of Federal Specification RR-S-550D, Type A, except for those provisions required of the contractor.

Rope Dia. (In.)	Structural Strand Dia. (In.)	Stock No. G-416 Galv.	Stock No. S-416 S.C.	Weight Each (lbs.)	Dimensions (In.) A	C	D	F	G	H	J	L	M	N
¼	—	1039619	1039628	1.10	4.56	.91	.69	.38	.69	1.56	2.25	1.56	1.31	.36
5/16-3/8	—	1039637	1039646	1.30	4.84	.81	.81	.50	.81	1.69	2.25	1.75	1.50	.44
7/16-1/2	—	1039655	1039664	2.25	5.56	1.00	1.00	.56	.94	1.88	2.50	2.00	1.88	.50
9/16-5/8	½	1039673	1039682	3.60	6.75	1.25	1.19	.69	1.13	2.25	3.00	2.50	2.25	.56
¾	9/16-5/8	1039691	1039708	5.83	7.94	1.50	1.38	.81	1.25	2.62	3.50	3.00	2.62	.62
⅞	11/16-3/4	1039717	1039726	9.65	9.25	1.75	1.63	.94	1.50	3.25	4.00	3.50	3.13	.80
1	13/16-7/8	1039735	1039744	15.50	10.56	2.00	2.00	1.13	1.75	3.75	4.50	4.00	3.75	.88
1⅛	15/16-1	1039753	1039762	21.50	11.81	2.25	2.25	1.25	2.00	4.12	5.00	4.62	4.12	1.00
1¼-1⅜	1 1/16-1⅛	1039771	1039780	31.00	13.19	2.50	2.50	1.50	2.25	4.75	5.50	5.00	4.75	1.13
1½	1 13/16-1¼	1039799	1039806	47.25	15.12	3.00	2.75	1.63	2.75	5.25	6.00	6.00	5.38	1.19
† 1⅝	1 5/16-1⅜	1039815	1039824	55.00	16.25	3.00	3.00	1.75	3.00	5.50	6.50	6.50	5.75	1.31
† 1¾-1⅞	1 7/16-1⅝	1039833	1039842	82.00	18.25	3.50	3.50	2.00	3.13	6.38	7.50	7.00	6.50	1.56
† 2-2⅛	1 11/16-1¾	1039851	1039860	129.00	21.50	4.00	3.75	2.25	3.75	7.38	8.50	9.00	7.00	1.81
† 2¼-2⅜	1 13/16-1⅞	1039879	1039888	167.00	23.50	4.50	4.25	2.50	4.00	8.25	9.00	10.00	7.75	2.13
† 2½-2⅝	1 15/16-2⅛	1041633	1041642	252.00	25.50	5.00	4.75	2.88	4.50	9.25	9.75	10.75	8.50	2.38
† 2¾-2⅞	2 3/16-2 7/16	1041651	1041660	315.00	27.25	5.25	5.00	3.12	4.88	10.50	11.00	11.00	9.00	2.88
† 3-3⅛	2½-2⅝	1041679	1041688	380.00	29.00	5.75	5.25	3.38	5.25	11.12	12.00	11.25	9.50	3.00
† 3¼-3⅜	2¾-2⅞	1041697	1041704	434.00	30.88	6.25	5.50	3.62	5.75	11.88	13.00	11.75	10.00	3.12
† 3½-3⅝	3-3⅛	1041713	1041722	563.00	33.25	6.75	6.00	3.88	6.50	12.38	14.00	12.50	10.75	3.25
† 3¾-4	—	1041731	1041740	783.00	36.25	7.50	7.00	4.25	7.25	13.62	15.00	13.50	12.50	3.50

† Cast Alloy Steel

APPENDIX E

FORTRAN PROGRAM

```
c     Fortran program to calculate the area of a
c     triangle in 3d space.
c     ID ---- matrix for element node numbers
        DIMENSION ID(3,550),X(350),Y(350),Z(350),S(550)
       READ (5,1) NN,NE
       DO 10 K=1,NN
       READ(5,2)IK,X(K),Y(K),Z(K)
   10  continue
       AREA=0.
       N1=0.
       N2=0.
       N3=0.
       AX=0.
       AY=0.
       AZ=0.
       BX=0.
       BY=0.
       BZ=0.
       CX=0.
       CY=0.
       CZ=0.
       DO 20 J=1,NE
       READ(5,3) IE,ID(1,J),ID(2,J),ID(3,J)
       N1=ID(1,J)
       N2=ID(2,J)
       N3=ID(3,J)
       AX=X(N2)-X(N1)
       AY=Y(N2)-Y(N1)
       AZ=Z(N2)-Z(N1)
       BX=X(N3)-X(N1)
       BY=Y(N3)-Y(N1)
       BZ=Z(N3)-Z(N1)
       CX=AY*BZ-AZ*BY
       CY=AZ*BX-AX*BZ
       CZ=AX*BY-AY*BX
       S(J)=.5*((CX*CX+CY*CY+CZ*CZ)**.5)
       AREA=AREA+S(J)
       write(6,4)J,S(J)
   20  continue
       WRITE(6,5)AREA
    1  FORMAT(2I8)
    2  FORMAT(I8,3F8.2)
    3  FORMAT(4I8)
    4  FORMAT(1X,I5,F10.4)
    5  FORMAT(1X,'TOTAL AREA IN FEET SQUARED',F10.4)
       STOP
       END
```

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