Shah Alam Sports Complex Design and Construction of Unistrut Space-frame Roof Structure

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The Shah Alam Sports Complex is a $100-million multiuse sports facility in Selangor, Malysia. The main feature of this complex is a 72000-seat multisport stadium. Seating on both sides of the stadium will be covered by a pair of barrel-vaulted acrylic sky roofs. Each roof is structurally supported by a Unistrut Space-Frame which in turn is supported at three of its four edges with a free span of 931 feet (284 m). The frame is cantilevered from the back 226 feet (69 m) over the seats.

In this paper, design philosophy to satisfy serviceability and ultimate limit states is discussed. Also discussed is the use of successive design approximations to create limited, but efficient, members data base that satisfies design requirements and does not burden, by its size, inventory control and construction. Effects of welding and galvanizing on cold-formed tubes are reviewed. Final analysis and design procedures of the structure and its supports are introduced, and the construction method is discussed.

1. Geometry:

Geometry of each of the crescent shaped arches is generated from a cut section of a circular cylinder. Each cylinder is of 814 feet (248 m) in radius and is tilted 10^o from the level ground. The front section is a 45^o cut measured from a horizontal plane where is the back section is a 23^o cut. Maximum distance between cuts is 226 feet (69 m), and the maximum height frame above playing field is 200 feet (61 m). Maximum span of the

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arch is 931 feet (284 m). Geometry of the space frame is depicted in figures 1 and 2. Each space-frame is composed of replicates of modular geometry. Each module consists of cold-formed steel tubes bolted into spherical steel nodes to form a rectangle-base pyramid. Figure 3 represents a typical Unistrut Space-Frame System III assembly. The base of each pyramid is a rectangle of 12.5 feet (3.8 m) in length and of 11.8 feet (3.6 m) in width. Depth of each pyramid is 9.9 feet (3 m). Cross sections of tubes are tapered towards the nodes using a truncated cone interface elements welded to the tubes. Cones provide for the transfer of forces from tubes to the connections, and reduce the sizes of the otherwise large nodes. A hexagonal bearing element "sleeve" is used between the cone and the node with a pin penetrating through the bolt and sleeve to allow for turning the bolt to engage into the node. Figure 4 represents a typical Unistrut Space-Frame System III tube assembly.

2. Supports:

Each of the two space-frames is supported in the back by prestressed concrete cantilever beams at 16 locations, and each side is supported by a prestressed concrete buttress at 8 locations. The total number of supports for each arch is 32 as shown on Figure 5. Stiffnesses and maximum reactions at supports were established a priori, and space-frame design has to satisfy these requirements.

3. Loading:

Space-frame is specified to be designed for the following basic load cases:

1- Space-frame:	15.50 psf (0.74 KN/m^2)
2- Gutter and glazing system:	5.25 psf (0.25 KN/m^2)
3- Lighting, catwalk, etc.:	1.50 psf (0.07 KN/m^2)
4- Floodlight:	1.00 Kip/ft (14.6 KN/m)

5- PA speaker:	2.00 Kip/ft at 50ft c.c. (29.2 KN/m at 15.2 m c.c)
6- Speaker cluster:	18.00 Kips (80.00 KN)
7- Live load:	10.50 psf (0.50 KN/m^2)
8- Point load:	3.50 Kips (15.6 KN)
9- Temperature:	86+40, 86-25 °F 30+22, 30-14 °C
10- Wind speed:	75 Mph with 50 year RP (33 m/sec.)
11- Horizontal support displacement:	0.75" (19 mm)

3.1. Wind Induced Loads:

For such a long span curved structure, it was deemed necessary to perform wind tunnel testing to establish the effects of wind. The following tests were performed on 1:300 scale models by RWDI Inc. in Toronto: pressure model test, pneumatic averaging test, and aeroelastic test. Results of these tests were implemented in determining the magnitude and distribution of mean wind loads on the roof of the stadium, the unbalanced loads induced by wind gust, and the affect of dynamic vortex shedding. Wind tunnel study model is depicted in Figure 6.

Prior to wind tunnel testing, local wind climatic data and vibration modes of the structure should be extracted. The results will be incorporated into wind tunnel data to predict the full scale wind pressures acting on the space-frame.

Utilizing the limited wind data available at Kuala Lumpur International Airport and Petaling Jaya, a statistical analysis was combined with wind tunnel tests to produce a 60 second and a 1 hour speed at 19 meter (62 ft) and at 58 meter (190 ft) for return periods of 10, 50, and 100 years. The resulting one hour speed of 80 Mph (35 m/sec.) at 58 meter (190 ft) for a return period of 100 years was adopted.

Of the 15 extracted mode shapes of vibration of the space frame, the first three, depicted in Figure 7, have the highest participation and are used for the dynamic wind load analysis.

Test results indicated an aerodynamically stable roof structure for wind speeds of magnitudes well beyond that for a 50 year return period. Wind load components and the resulting wind induced load cases are given in Figure 8.

3.2. Loading Combinations:

To satisfy serviceability limit state requirements, 10 service load combinations were established to predict service load deflections. Serviceability requirements require cambering the space-frame by dead load deflection, and a maximum vertical wind induced displacements of 9 inches (229 mm).

To satisfy ultimate limit state requirements, the space-frame is designed for 63 different factored load combinations.

4. Space-Frame Design:

The space-frame was designed using an in-house computer program " USSP" developed by Unistrut Space-Frame Systems, Inc. USSP is an integrated geometry generation, structural analysis, structural design, plotting, and manufacturing data generation program. Prior to structural design a member assembly data base is generated.

4.1. Data Base Generation:

The data base is a set of member assemblies and nodes (Figures 3 and 4, Table 1) designed to efficiently satisfy strength requirements. For such large structure (5556 nodes and 21550 members), selecting the right material is an essential part of the design process that will highly reflect on its efficiency. For chords and web members, cold-formed high strength structural tubing was selected. Tubes are hot-dipped galvanized on both sides to provide for maximum protection against corrosion. The tube-cones assembly is galvanized before inserting the bolts into the tubes. A tube-cones assembly is produced by welding a cone to each end of the tube, Figure 4. An access hole has to be provided at the end of each tube for bolts insertion after galvanization. Cold-formed structural steel tubes lose some of their strength acquired by cold-working at weld locations. In tension, bolt sizes were selected as the minimum required by tensile strength requirements. This is to keep the node sizes small. Tensile strength of the tube assembly may also be governed by the strength of tube assembly at the access hole location where no affect of welding. Area of the access hole ranges from 9 to 30% of the tube gross section area. In compression, the effect of the heat affected zone is less than the affect of local yielding at hole location. Tests were performed to establish the effect of access holes on the buckling behavior of tubes. Results are given in Figure 9. The effect of access holes on buckling behavior of tubes is more pronounced in the short to medium column range.

A data base of 100 member assemblies was initially generated. Structural analysis was performed and member forces calculated. Based on these member forces a more efficient data base, consists of only 40 tube assemblies ranging in diameter from 3" (76 mm) to 16" (406 mm), was generated to reduce part numbers and to provide for fabrication and erection efficiency. A summary of the data base is given in Table 1.

Bolts, sleeves, cones, and welds were designed for their relevant stress states.

The following issues were of paramount importance in designing the data set:

- Local buckling of tubes
- Column buckling of tubes

4.1.1. Local Buckling of Tubes:

It is of structural and economical concern to design a database with tubes of minimum thickness. This will provide for tubes of less weight and higher radius of gyration for the same tube diameter. However, reducing the thickness beyond a limit value, for a given tube diameter, may make the tube vulnerable to local buckling. For cylindrical tubes, the inward buckling causes superimposed transverse compression membrane stresses, and the buckling form itself is unstable. As a consequence of the compression membrane stresses, buckling of an axially loaded cylinder is coincident with failure and occurs suddenly, accompanied by a considerable drop in load (snap-through buckling) [3]. For tubes use in the subject project L_{min}= 141.6", $(Rt)_{max}$=3.304 in^2, and $Z_{min} = 5789.42$ where $Z = \frac{L^2}{Rt}\sqrt{(1-\mu^2)}$. Z=5789 >> 50, and the tube will buckle as a column [3].

Also, based on Plantema's representation [3] of strength of cylindrical tubes for local buckling, collapse stress occurs at yield point where $\frac{3700}{F_y} = 66 > \left(\frac{D}{t}\right)_{max} = 48.1$. For each tube used, local buckling will not occur before yielding, and no reduction in allowable stress is necessary.

Each tube used satisfy the AISC [1] requirement of $\left(\frac{D}{t}\right)_{max} = 48.1 \ll 0.441\frac{E}{F_y} = 229$.

British Standards [2], however, classify a circular hollow tube subject to moment or axial compression to be plastic if $\frac{D}{t} \leq 40\left(\frac{275}{p_y}\right)$, where p_y is the design strength of steel. A plastic section is one that is capable of developing a full plastic moment capacity without local buckling distress. Most of the tubes used satisfy this requirement. p_y was reduced for the tubes with D/t that does not satisfy this requirement.

4.1.2. Column Buckling of Tubes:

Tubes under compression were designed using B.S. specifications. However, in addition to using a reduced p_y to account for local buckling, the following formula was extracted from test results to account for affect of access hole on column strength:

$$P_{y_e} = F_y\left[1.36275 - \frac{\frac{KL}{r}}{366.166} - \frac{\frac{d}{t}}{87.928} - 0.467296\frac{F_y}{F_u}\right]$$

Where :

p_{y_e}: experimental compressive design strength d: diameter of erection hole

F_y: Yield stress

F_u: Ultimate stress

p_y used in design is the minimum of p_{y_e}, p_y stipulated by the code, F_y, or $0.84F_u$.

4.2. Structural Analysis:

For the different load combinations given earlier, a static structural analysis was performed, and member and node sizes were selected accordingly. Although Unistrut space frame systems have an inherent high degree of redundancy, structural analyses were performed on the space-frame with some members eliminated to insure that the structure have several alternate load paths. For global buckling stability, a linear buckling analysis was performed for two different load cases: dead load + increased live load and dead load + increased unbalanced wind load. Factor of safety against buckling instability in each case exceeds 2.

5. Construction:

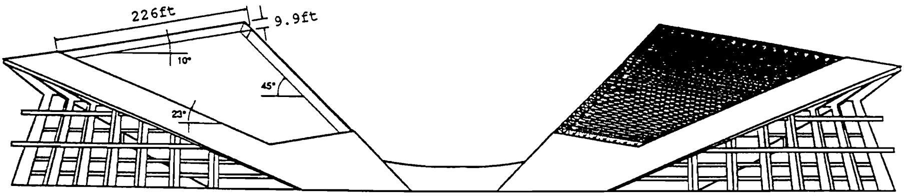
Space-frame is being constructed by strips extending between the back support and the front arch of the frame. Each strip is secured between two adjacent supports to insure its relative position. Strips are supported by temporary shoring towers between the supports and the front arch of space-frame. Each tower is equipped with a screw-jack to fine-tune the relative position of space-frame and to enable cambering the frame by its dead load deflection. Strips are tied together as they are extended towards the front arch of the frame. This is to preserve the arch action of the frame which provides a self-supporting mechanism.

6. Conclusions:

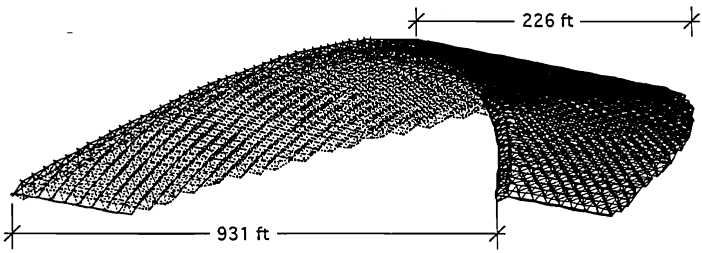
Space-frame structures provide flexible and efficient means to satisfy mostly any architectural and structural requirements. Using the appropriate system, material, and technology, space-frames offer a most attractive and cost effective structural system, and possibly challenge the conventional concrete or steel systems. Being constructed of structurally proportioned modular building blocks, the only limitation on space-frames is the designer's imagination.

7. References:

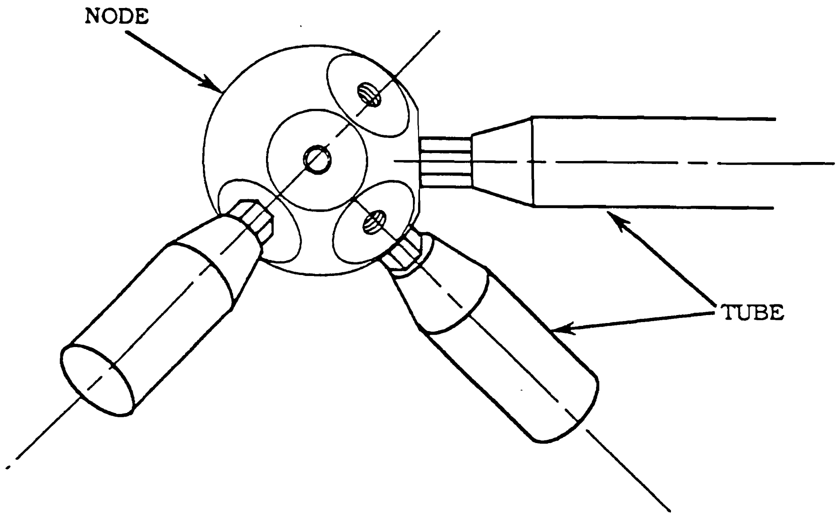
1. AISC, '*Cold-Formed Steel Design Manual,*' 1986.
2. BS 5950: Part 1: 1985, '*Structural Use of Steelwork in Buildings.*'
3. Yu, Wei-Wen, '*Cold-Formed Steel Design,*' John Wiley & Sons, 1985.



- Figure 1 -

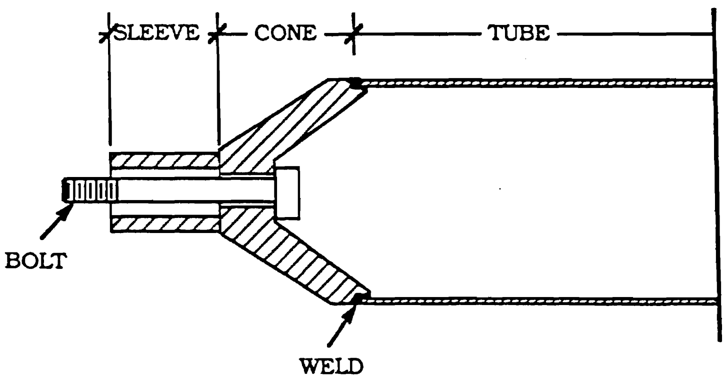


- Figure 2 -



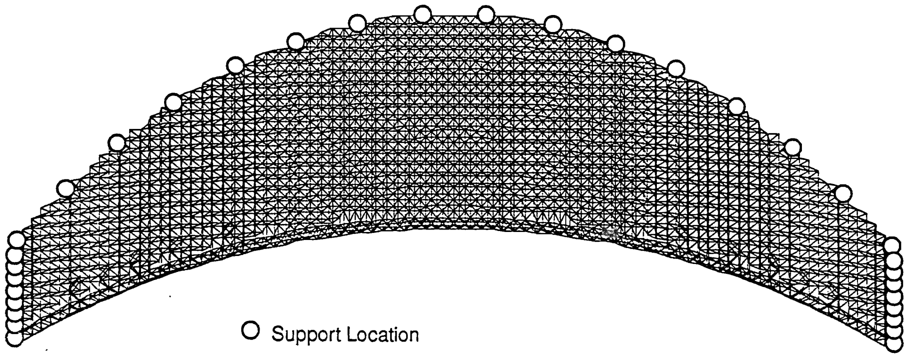
SPACE FRAME ASSEMBLY

- Figure 3 -

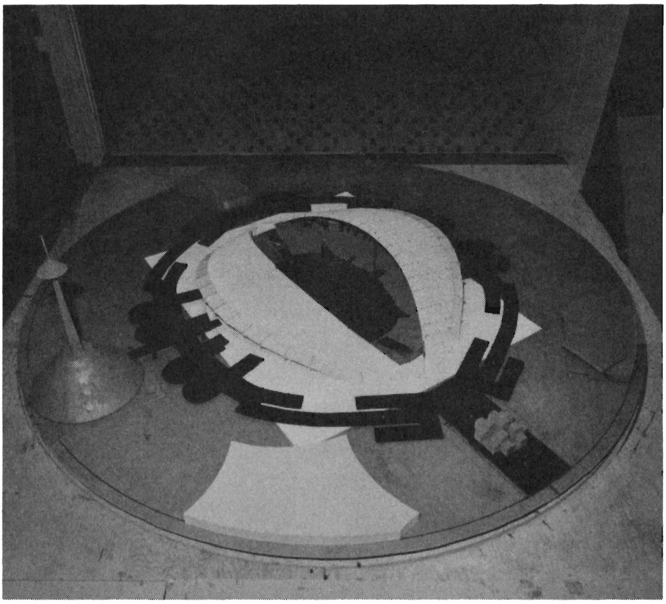


TUBE ASSEMBLY

- Figure 4 -

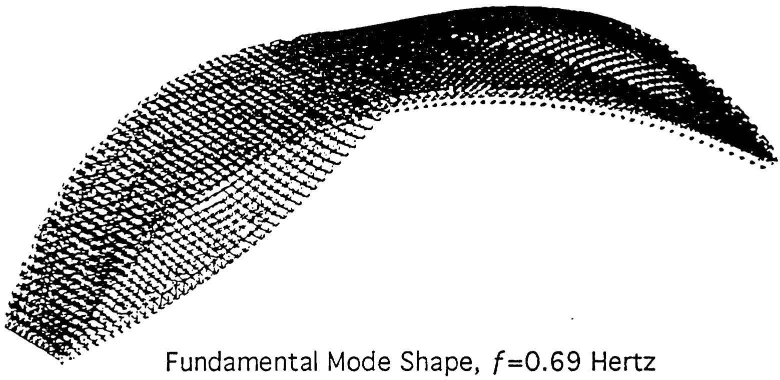


- Figure 5 -

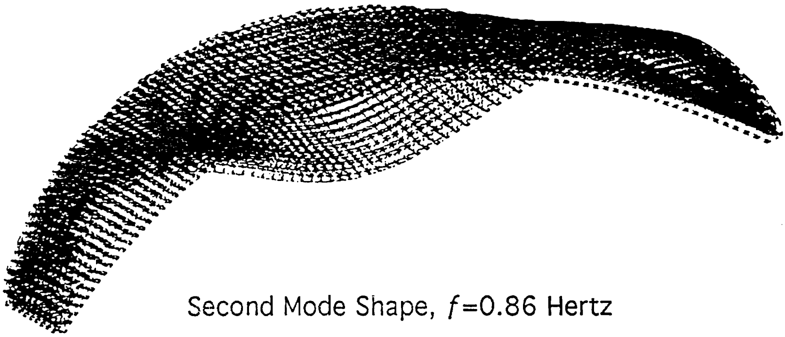


Model in Wind Tunnel

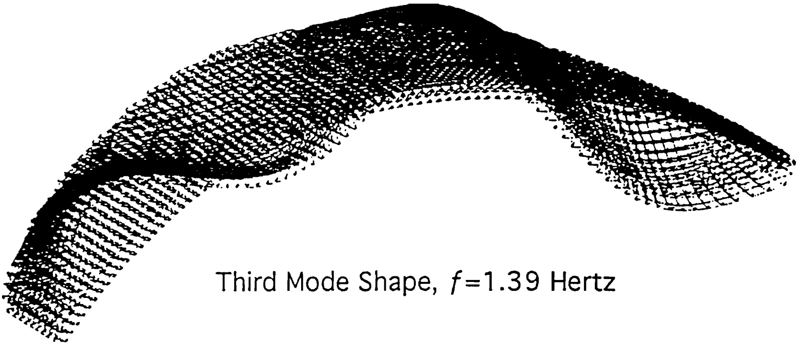
- Figure 6 -



Fundamental Mode Shape, f=0.69 Hertz

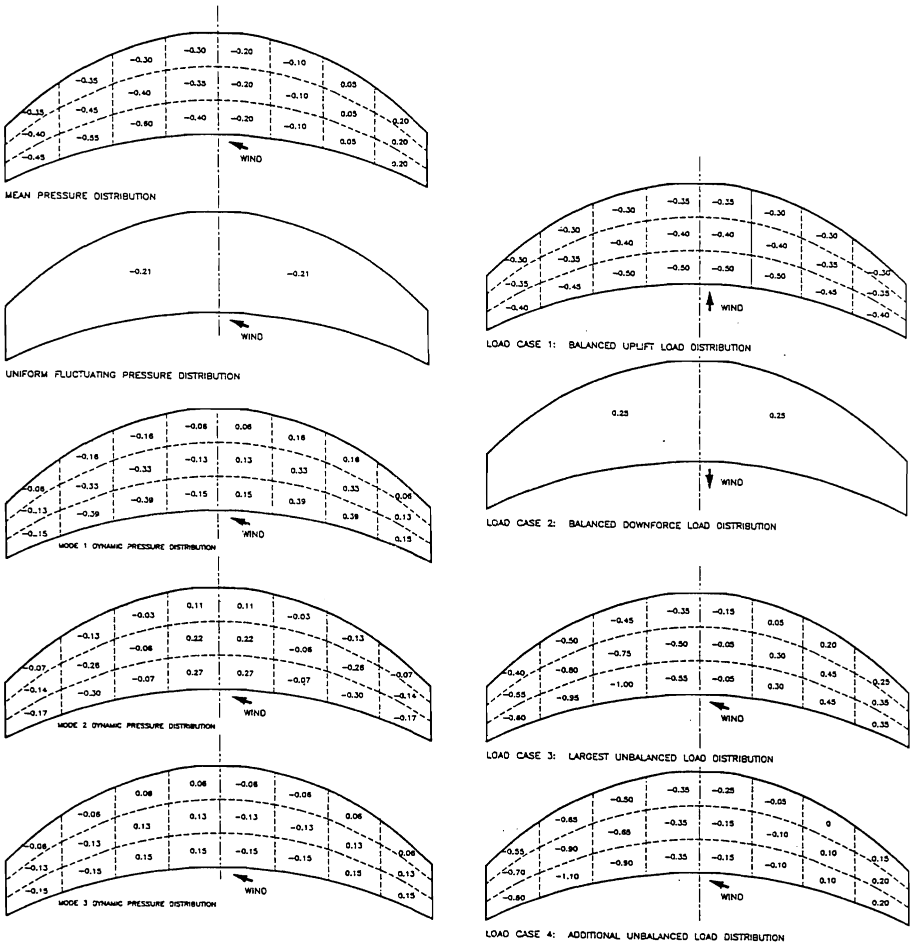


Second Mode Shape, f=0.86 Hertz

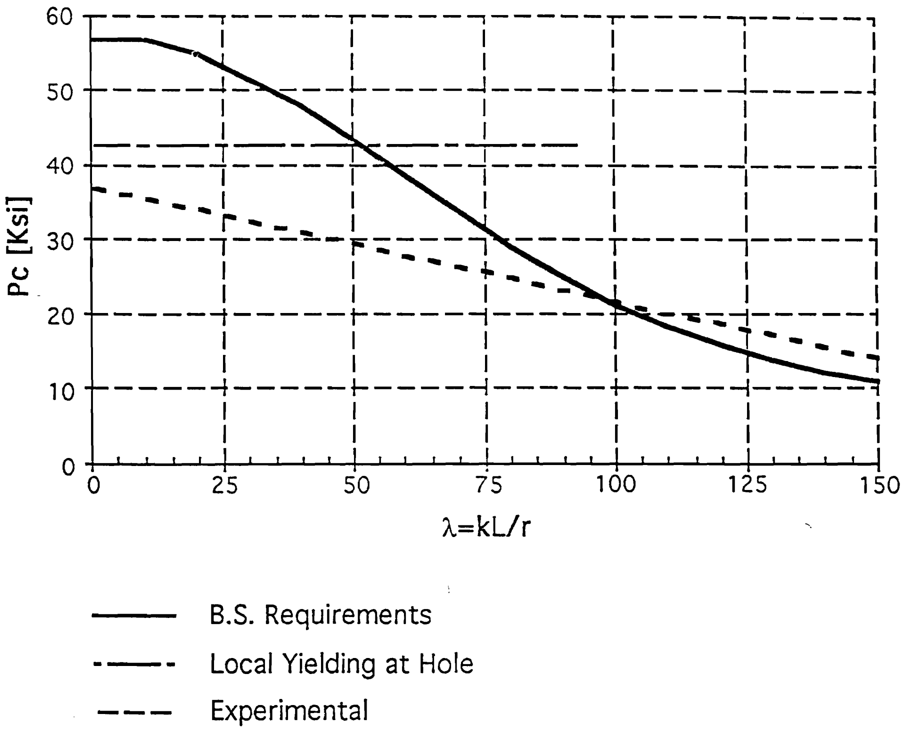


Third Mode Shape, f=1.39 Hertz

- Figure 7 -


MEAN PRESSURE DISTRIBUTION
WIND
UNIFORM FLUCTUATING PRESSURE DISTRIBUTION
MODE 1 DYNAMIC PRESSURE DISTRIBUTION
MODE 2 DYNAMIC PRESSURE DISTRIBUTION
MODE 3 DYNAMIC PRESSURE DISTRIBUTION
LOAD CASE 1: BALANCED UPLIFT LOAD DISTRIBUTION
LOAD CASE 2: BALANCED DOWNFORCE LOAD DISTRIBUTION
LOAD CASE 3: LARGEST UNBALANCED LOAD DISTRIBUTION
LOAD CASE 4: ADDITIONAL UNBALANCED LOAD DISTRIBUTION

- Figure 8 -



COMPRESSIVE STRENGTH OF TUBES

- Figure 9 -

UNISTRUT SPACE-FRAME SYSTEM III COMPONENT DATASET FOR THE MAIN STADIUM ROOF OF THE SHAH ALAM SPORTS COMPLEX

	TUBES			BOLTS		SLEEVES			STRENGTH	
Assembly Designation	Outside Diameter [mm]	Wall Thickness [mm]	Hole Diam. [mm]	Bolt Diam. [mm]	Pin Diam. [mm]	Length [mm]	Outside Diameter [mm]	Inside Diameter [mm]	**Tension [Kips]**	**Comp.* [Kips]**
76 c	76.3	2.8	25	16	4	34	24	17	**13.9**	**11.2**
76 d	76.3	2.8	32	20	5	34	27	22	**21.7**	**11.2**
89 a	89.1	2.8	25	16	4	34	27	17	**13.9**	**17.3**
89 b	89.1	2.8	32	20	5	34	30	22	**21.7**	**17.3**
89 c	89.1	3.2	38	24	5	45	35	26	**33.6**	**19.6**
102 a	101.6	2.8	32	20	5	34	32	22	**21.7**	**24.8**
102 b	101.6	3.2	38	24	5	45	36	26	**33.6**	**28.0**
114 a	114.3	3.2	32	20	5	34	36	22	**21.7**	**38.1**
114 b	114.3	3.2	38	24	5	45	41	26	**33.6**	**38.1**
114 c	114.3	3.2	46	27	5	50	41	29	**44.2**	**38.1**
102 d	101.6	4.0	51	30	5	58	41	32	**56.2**	**34.3**
114 d	114.3	3.6	46	27	5	50	46	29	**44.2**	**42.5**
114 f	114.3	4.0	38	24	5	45	41	26	**33.6**	**46.8**
114 e	114.3	4.0	46	27	5	50	46	29	**44.2**	**46.8**
114 g	114.3	4.0	46	30	5	58	46	32	**56.2**	**46.8**
114 h	114.3	4.0	78	42	6	75	54	44	**90.3**	**46.8**
114 k	114.3	4.5	38	24	5	45	46	26	**33.6**	**52.1**
114 j	114.3	4.5	46	27	5	50	46	29	**44.2**	**52.1**
114 l	114.3	4.5	48	30	5	58	46	32	**56.2**	**52.1**
140 a	139.8	3.6	56	36	6	66	54	38	**81.1**	**69.2**
140 b	139.8	4.0	56	36	6	50	54	38	**81.1**	**76.4**
140 c	139.8	4.5	46	30	5	58	54	32	**56.2**	**85.2**
140 d	139.8	4.5	70	42	6	82	60	44	**112.4**	**85.2**
165 b	165.2	4.5	46	30	5	58	60	32	**56.2**	**121.9**
165 a	165.2	4.5	56	36	6	66	65	38	**81.1**	**121.9**
140 g	139.8	6.0	75	42	6	82	65	44	**112.4**	**110.9**
140 h	139.8	6.0	110	52	6	105	75	54	**152.6**	**110.9**
191 a	190.7	4.5	65	42	6	66	75	44	**112.4**	**155.0**
165 c	165.2	6.0	65	42	6	82	75	44	**112.4**	**159.6**
216 a	216.3	4.5	73	48	6	82	80	50	**147.7**	**176.1**
165 d	165.2	7.0	75	48	6	66	80	50	**147.7**	**183.9**
191 c	190.7	6.0	73	48	6	82	80	50	**147.7**	**209.6**
191 b	190.7	6.0	100	60	6	105	90	62	**241.4**	**197.1**
191 e	190.7	7.0	65	42	6	82	85	44	**112.4**	**242.3**
191 d	190.7	7.0	73	48	6	82	85	50	**147.7**	**242.3**
216 c	216.3	8.0	79	52	6	95	95	54	**176.4**	**339.4**
267 d	267.4	9.0	92	60	6	105	110	62	**241.4**	**488.7**
267 e	267.4	9.0	100	66	6	126	115	68	**296.8**	**482.4**
356 b	355.6	12.0	132	87	6	126	150	89	**535.7**	**826.1**
406 a	406.4	12.0	159	105	6	126	166	108	**780.8**	**931.7**

*** COMPRESSIVE STRENGTH IN THIS TABLE IS BASED ON A TUBE LENGTH OF 150".**

- Table 1 -