CONCEPTUALIZATION, DESIGN AND ERECTION OF A SMALL SCALE CABLE-DOME STRUCTURE

by

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ABSTRAK

Projek ini bertujuan untuk memahami mengenai rekabentuk dan pembinaan struktur kubah kabel. Pengenalan mengenai perumusan asas untuk menjalankan analisis ke atas struktur kubah kabel dengan menggunakan kaedah mod tekanan seimbang-diri. Kemudian, analisis dijalankan ke atas empat model yang berlainan. Akhirnya, keputusan analisis yang diperoleh ditunjukkan. Nilai tegangan yang sesuai untuk setiap anggota struktur dengan merujuk kepada keputusan mod tekanan seimbang-diri telah dikaji dengan membina tiga model mini dan satu model percubaan sepanjang 3 m. Semasa pembinaan, urutan untuk setiap model telah dikaji dengan teliti.

ABSTRACT

The main objective of this project is to gain insight about the design and erection sequence of cable-dome structures. Basic formulation of the analysis to determine self-equilibrium stress mode for cabled dome structure is first introduced. Analyses have been carried out on four different models. Design based on output obtained from analysis is then shown. Based on the design, appropriate amount of pre-tension to members of cable dome structure have been studied by means of actual construction of three mini-scale models and one trial model of 3 m span. The sequence of pre-tensioning process is also observed and shown.

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CHAPTER 1
INTRODUCTION

1.1 Cable dome structure

Cable dome structures become the focus of contemporary researchers due to people's pursuit in light weight forms which widely used for covering large space. Cable domes, first proposed by Geiger et. Al. (1986), belong to the indeterminate and prestressed assembly and were believed to be the inspiration of the 'Tensegrity Principle', which was first enunciated by Buckminster Fuller. Tensegrity means tension integrity, a phenomenon which can be described as a compression elements becoming the 'small island in a sea of tension'.

For tens of years, tensegrity systems were developed to realize the dream despite the fact that the actual structural efficiency is not high as expected. An original and strict definition of tensegrity structure is that it should consist of physically continuous cables (structural elements in tension) and discontinuous struts (structural elements in compression). Although the history of this class of structures could be traced back to the tensegrity system conceived by Fuller over half a century ago, their structural potentials have not been exhibited until the applications of cable domes for 1988 Seoul Olympics by Geiger et. al..

Cable-dome demonstrated structural efficiency in many long span roofs application. They are able to not only save cost of the construction but also create a structure which is light. Such advantages are ideal for the construction of building which require large free space such as multi-purpose hall, swimming pools, stadium etc.. In recent years, some new types of such structures, which are hardly classified as cable domes, have been built such as the canopy of the Busan Stadium used in the 2002 South Korea FIFA World Cup, the canopy of the Kuala Lumpur Outdoor

Stadium in Malaysia (Picture 1.1 and Figure 1.1) etc. Many so-called tensegrity structures nowadays developed from this basic idea do not satisfy the definition exactly. The terminology of tensegrity structure used is this study denotes a free-standing prestressed pin-jointed cable-strut system, which is in a self-equilibrium state as mention in paper by Zhang and Ohsaki (2005).

Picture 1.1: Bukit Jalil Stadium at Kuala Lumpur, Malaysia

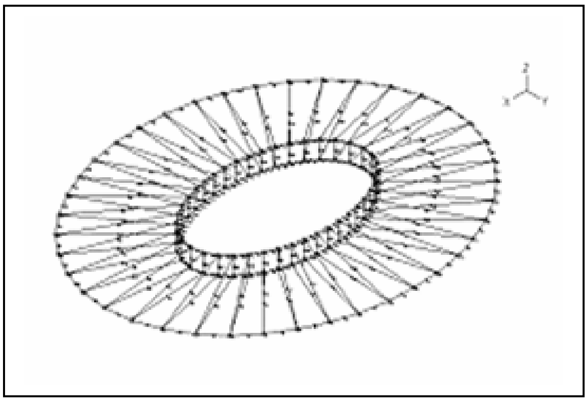


Figure 1.1: Roof system of Bukit Jalil Stadium

Cable-dome is a stand alone structure which achieves its span by means of continuous tension cables with discontinuous compression masts. Loads are carried from a central tension ring through a series of radial ridge cables and intermediate diagonals until they are connected to a perimeter compression ring (as shown in Figure 1.2). The post is supported at by intersection with diagonal cables which attached to the compression ring.

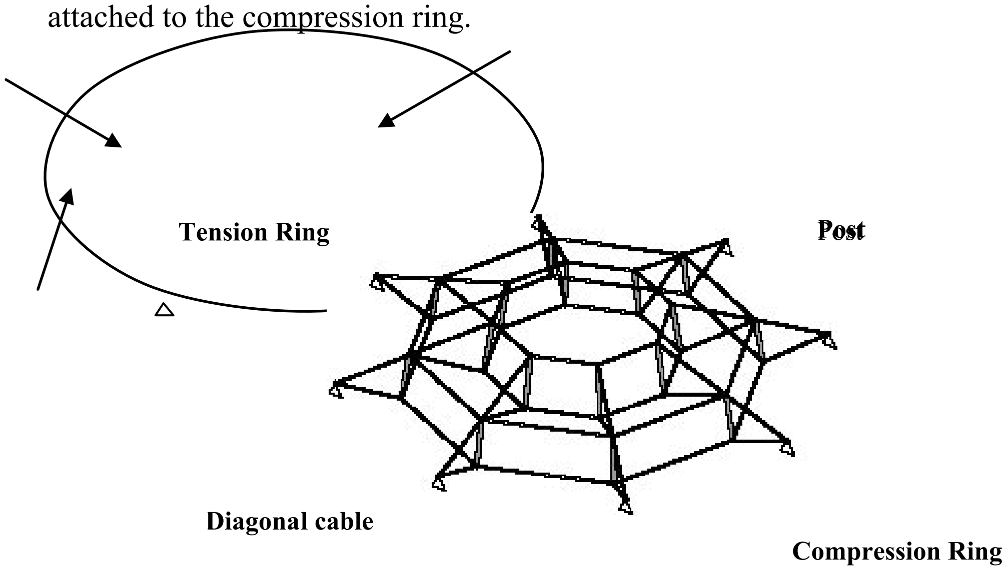


Figure 1.2: Typical cable dome

To design this class of structure, conventional analytical means of prediction of system instabilities are useless as a consequence of their non-linear behaviour and reliance upon geometric stiffness. Therefore, an analytical analysis has to be carried out to iterate to a condition where no compression cables existed in this system.

Beside that, the construction of this kind of building is challenging. A cable-dome needs to be prestressed to compensate for the tendency of cables to go slack. But, the assemblages of these cables are unstable when in the process of construction before the application of pre-tension. Therefore, a specific sequence to construct the entire structure is required.

1.2 Literature review

1.2.1 Introduction

Cable Dome is an innovative structure that mainly consists of cables and struts have been erected in many large scale buildings worldwide, and been eye-catching for their special structural configurations and long-span capabilities. Since such structures are usually prestressed, the generic name 'cable-strut tensile structure (CSTS)' is used to define this type of structure (Deng et. al. (2005). Studies on CSTS, mainly for cable domes, have been carried out widely, including analysis of geometrical configuration and stability, initial prestressed states, structural behaviour under external loads and structural optimization etc.

1.2.2 Conceptualization and design

Cable-dome is a new structural form that has become popular in the construction of long-span roof structure. Their configuration is complicated and hence special sequential to the sequence of construction consideration in the structural conceptualization and design is needed.

Lamella Suspen-dome is one type of a cable dome which is very slender and light weight. There are numbers of paper discussing the various aspects or configurations design of this kind of structure. The papers written by Kitipornchai et. al. (2005) includes the method for designing cable prestress force, a simplified analysis method, and the estimation of buckling capacity. This paper presents the findings of an intensive buckling study of the Lamella suspend-dome system that takes geometric imperfection, asymmetric loading, rise-to-span ratio, and connection rigidity into consideration. Finally, a suggested design and construction guidelines are also given in the conclusion of this paper.

Another paper by Kang et. al. (2003) which addresses the analysis and design issues of the suspen-dome structural system presents a simple design method for calculating the prestress forces in the cables of suspend-dome structures. In the paper, emphasis is made in a particular case of the suspen-dome system – the outmost-ring stiffened suspend-dome structure.

Besides that, Gao and Weng (2004) present paper that discuss about orthogonal design method which was employed to investigate the prestressed cables sensitivity to the suspend-dome system. Parametric studies were carried out to study the sensitivity of the structure's static behaviour, dynamic and buckling loads when the prestresses in the cables varied.

Analysis about the geometric stability analysis and the optimal prestress design are very important to understand the behaviour of cable domes. A new specific equilibrium state of integral feasible prestress is presented and by applying this specific state, the geometric stability analysis algorithm is modified and the optimal prestress of the domes is also designed. This study is done by Yuan and Dong (2003). A study on optimization for maximum stiffness of a full-scale cable dome, which has a 240 x 190 m elliptic plan and is roofed with membrane, is presented by Kawaguchi et. al. (1999). The optimization performed in this study indicated that the optimum shape of the dome depends greatly on the length of the outermost posts. Such a representation is very useful for designers to evaluate the dependence of the optimality upon the design parameters so as to make design decisions accordingly

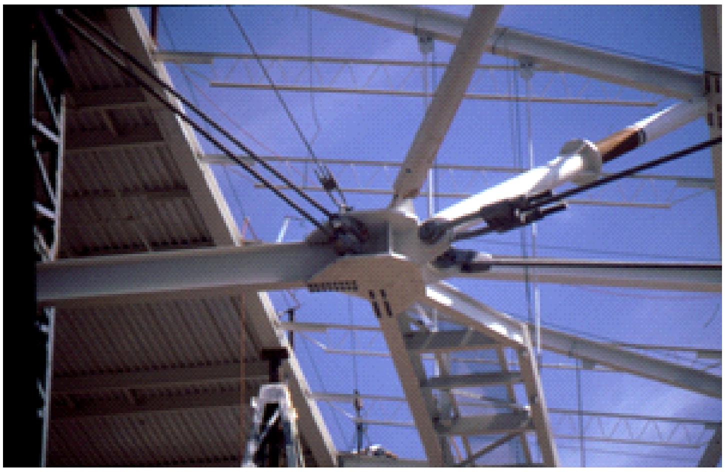
Apart from the above mentioned research work, analysis related to the static and dynamic behavior of a cable dome (Gasparini et. Al. (1989)) and geometric nonlinear problem (Tang et. al. (1998)) was also studied. Other paper written by Luo and Shen (2004) concentrated on the geometric configuration and component stress variation in the process of the construction of cable dome which is based on the study on the cable dome's null stress condition and construction initial configuration.

Determination of self-equilibrium stress mode of cable dome structures is a key step in the design of cable dome structure. In a study by Amrita (2004), analysis has been conducted using specialized computer software called TCSELF, on 18 different models of various types of shapes as well as openings, both concentric and eccentric. Another paper by Liew et. al. (2003) investigated the problem of shape finding of cable-strut assemblies which could be incomplete with missing or slack cables and cables with lengths greater than eventual assembled length.

There were quite a numbers of research works done on the aspect of analysis of the various types of domes using different computational method. Moreover, analysis studies about different factors affecting the cable dome system were also being conducted. But, the analysis and studies on the methods of the cable domes erection were very little.

1.2.3 Erection

Cable dome have become larger in line with advantages in design and construction technologies. The challenge for engineers was to develop constructible details and maximize their repetition for economy, despite the complicated geometry. One potential disadvantage of cable strut structures is that the joining methods may be more complicated, as both hollow sections and cables have to be connected at one node (Picture 1.2), compared with the use of circular hollow section for space trusses.



Picture 1.2: Connection of hollow section and cables at a node

Several methods of construction regarding the cable dome prestress structure were being studied for various types of cable dome structure includes the Gymnastics and Fencing Arenas for the Korean Olympics (Geiger et. al. (1986)) and Lamella suspen-dome, which is very slender and light weight. Construction guidelines for Lamella suspen-dome are discussed at the end of the papers studied by Kitipornchai et. al. (2005).

Cable-strut structures are constructed from a system of short struts interconnected by high-tensile cables, providing lightweight structures with large-span capability (Liew et. al. (2003)). The two novel cable strut systems constructed using star prism (SP) and di-pyramid (DP) grids are to extend cable nets structures into freestanding grids. The SP and DP systems show promise of having lower weight-to-strength ratios than conventional space truss systems. They are also structurally more efficient for long-span spatial applications. Finally, innovative joint details are proposed considering the ease of fabrication and erection of spatial structures.

The proper installation sequence during the construction of the cables is the key step for erecting a cable-dome structure which will function satisfactorily. In practical engineering, it is difficult to ensure that the designed prestresses of cables have been exactly introduced into the structures at site. Moreover, a cable dome structure is an unstable structure during the construction process. So, a specific study about the erection sequence of CSTS has been conducted by Deng et. al. (2005).

1.2.4 Summary

Cable dome structure is a new technology born from the principle of tensegrity. It is economical structure which is light in weight and can cover a large space. Cable dome is the ideal answer for the design of building such as stadium, swimming pool etc. as its unique and aesthetic look may light up the beauty of the whole structure. But, the construction of this kind of building is challenging. A study of the erection sequences have to be conducted in the way to provide a safe and fast way to assemble the structure which with function satisfactorily. Numbers of paper concerns the erection of the other type of the cable dome structure have been conducted. Yet, the studies about the erection sequence of the type of cable dome structure considered in this study (or cable-struts system) have not been reported.

1.3 Objectives

The objective of this project is to gain insight into the concept of design and Construction of cable dome structure. Furthermore, it is also carried out in to verify the results of analysis on self-equilibrium stress mode and to gain understanding of the construction sequence of cable dome structure.

CHAPTER 2

METHODOLOGY

2.1 Analysis of self-equilibrium stress mode

2.1.1 Introduction

Cable dome structure is a self-equilibrium structural system. It is called self-equilibrium since the cable-post system will be in equilibrium due to pre-stress introduced prior to the imposition of any external loading. Pre-stress must be introduced according to a specific proportion among different structural members. The specific proportions to be used can be determined by means of an analysis called self-equilibrium stress mode analysis. The proportion's result will be given in term of stress ratio among members of the structure. One of the method of analysis which is elegant from the point of view of basic formulation of equations to be solved is a method proposed by Tanaka and Hangai(1986) and Hangai and Kawaguchi(1991). The method has been used in a number of research work such as Oda and Hangai(1995), Sugiuchi et al(1998) and Choong et al(2000). Further research works on the applicability of the method have also been conducted by Tan(2001) and Amrita(2004).

2.1.2 Basic formulation

For the purpose of self-equilibrium stress mode analysis, a cable dome structure can be modeled as space truss system using a simple two-node truss element in 3-D as shown in Figure 2.1 where n_α: axial force in element α, f_{ix}, f_{iy}, f_{iz} and f_{jx}, f_{jy}, f_{jz} : component of n_α in global x, y and z direction at node i and j, respectively.

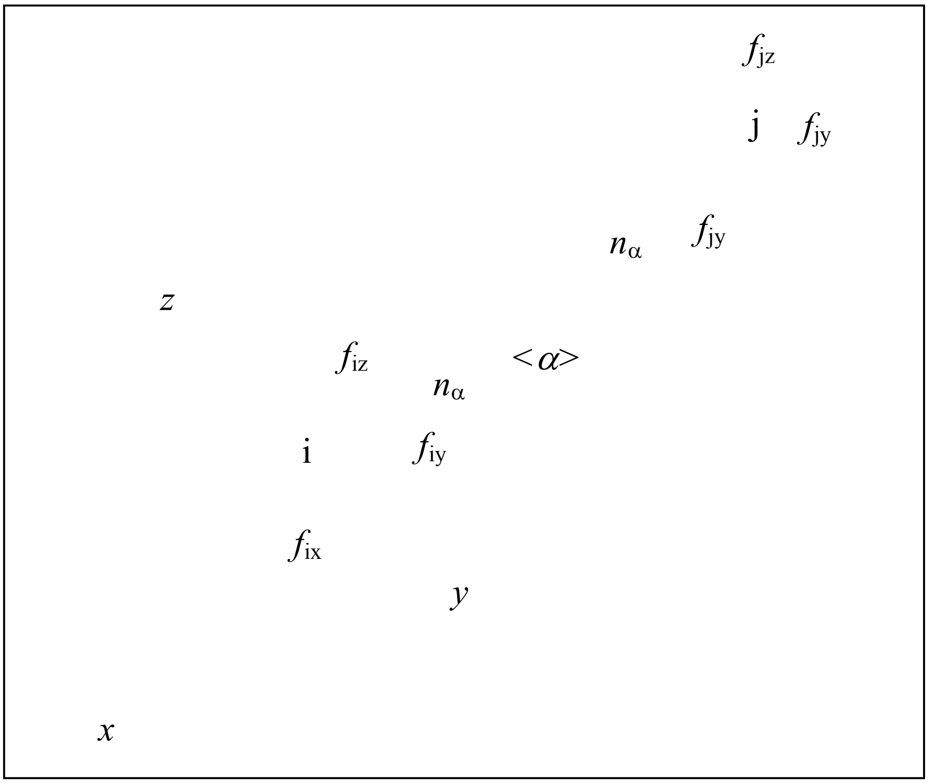


Figure 2.1: Two-node truss element in 3-D

Denoting the vector of directional cosines of the axis of truss element α with respect to global x, y and z axis as $\boldsymbol{\lambda}_{\alpha}$, vector of components of axial force n_α at node i and j as $\boldsymbol{f}_{i\alpha}$ and $\boldsymbol{f}_{j\alpha}$, respectively, the equilibrium equation at node i and j for the truss element could be expressed as follows:

$$-\boldsymbol{\lambda}_\alpha \boldsymbol{n}_\alpha = \boldsymbol{f}_{i\alpha} \qquad \textbf{(2.1a)}$$

$$\boldsymbol{\lambda}_\alpha \boldsymbol{n}_\alpha = \boldsymbol{f}_{i\alpha} \qquad \textbf{(2.1b)}$$

Collecting similar equations as shown in Equation (2.1a) and (2.1b) above for all members, the set of equilibrium equations for the whole analysis model could be expressed in matrix equation as follows:

$$\boldsymbol{Bn} = \boldsymbol{p} \qquad \textbf{(2.2)}$$

where ***B*** : rectangular matrix with size N × m, N: total number of degrees of freedom, m : total number of elements, ***n*** : vector of axial forces n_α (α=1,..,m) and ***p*** : vector of external nodal force. The self-equilibrium stress mode will be given by the solution to Equation (2.2) with **p=0**. Setting **p=0** in Equation (2.2) will the yield the following equation:

$$\boldsymbol{Bn} = \boldsymbol{0} \qquad \textbf{(2.3)}$$

For the determination of self-equilibrium stress mode, it should be remembered that the desired shape is known. Hence ***B*** is known since the content of ***B*** depends solely on the shape of the analysis model which is an assemblage of truss elements. Thus, the problem of determination of self-equilibrium stress mode could be stated as follows:

"Find vector ***n (≠0)*** which satisfies Equation (2.3)".

Equation (2.3) is a homogeneous equation with coefficient matrix ***B*** being a rectangular matrix. Making use of the concept of generalized inverse of a general rectangular matrix, solution to Equation (2.3) can be elegantly expressed as follows:

$$\boldsymbol{n} = \left[\boldsymbol{I}_m - \boldsymbol{B}^+\boldsymbol{B}\right]\boldsymbol{\beta} \qquad \textbf{(2.4)}$$

where $\boldsymbol{I_m}$: identity matrix of size m×m, $\boldsymbol{B}^+$: Moore-Penrose generalized inverse for ***B*** and $\boldsymbol{\beta}$: arbitrary vector of coefficients of size m. Matrix [$\boldsymbol{I_m}$-$\boldsymbol{B}^+\boldsymbol{B}$] in Equation (2.4) could be rewritten using the m column vectors $\boldsymbol{g_i}$ as follows:

$$\left[\boldsymbol{I}_m - \boldsymbol{B}^+\boldsymbol{B}\right] = \left[\boldsymbol{g}_1 \quad \boldsymbol{g}_2 \quad \cdots \quad \boldsymbol{g}_{m-1} \quad \boldsymbol{g}_m\right] \qquad \textbf{(2.5)}$$

Assuming that the matrix [$\boldsymbol{I_m}$-$\boldsymbol{B}^+\boldsymbol{B}$] contains q linearly independent vectors $\mathbf{h_1}$**,** $\mathbf{h_2}$**,** $\mathbf{h_3}$**, … ,** $\mathbf{h_{q-1}}$ **and** $\mathbf{h_q}$, then Equation (2.4) could be rewritten as follows:

$$n = \mu_1 h_1 + \mu_2 h_2 + ... + \mu_{q-1} h_{q-1} + \mu_q h_q \qquad \textbf{(2.6)}$$

where μ_j (j=1, 2…, q) are arbitrary coefficients. The value q will give us the number of linearly independent self-equilibrium stress mode. It can be shown that the number q is equal to the degree of statically determinacy of the cable dome structural system under investigation. Since q=0 means that a structure is statically determinate, it can be concluded that in order for a cable dome structure to be structurally possible, it must be at least statically determinate to the first degree, i.e. q=1.

In those cases when $q \geq 2$, ratio of coefficients β_j in Equation (2.6) can be determined by means of optimization against certain prescribed criteria such as stability and increase in initial stiffness as summarized in the research works by Oda et al(1995) and Sugiuchi et al(1998).

2.1.3 Self-equilibrium stress mode analysis

Take a rectangular shape model with concentric opening in the middle as an example to show the format of the input and output data (Figure 2.2).

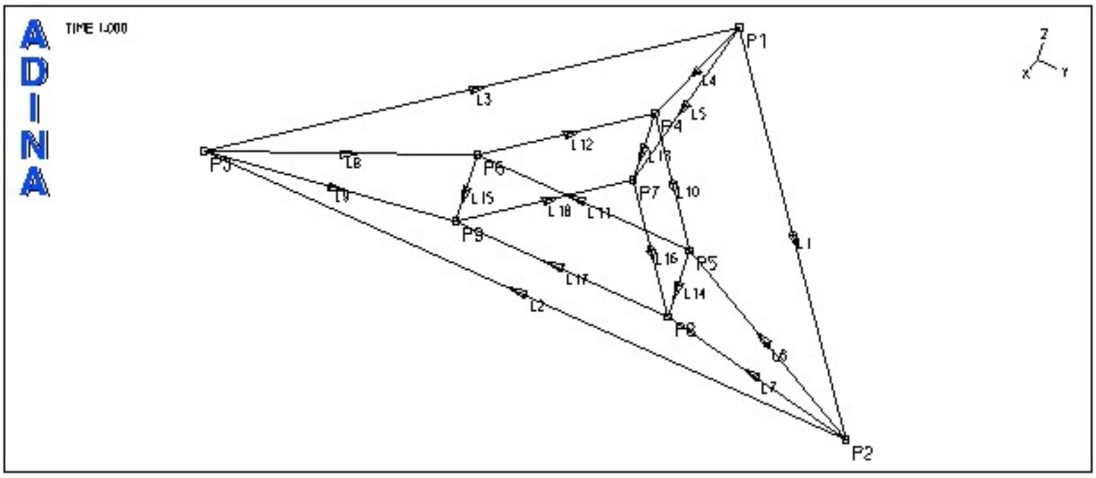


Figure 2.2: An illustrative example for self-equilibrium stress mode analysis

Analysis to determine the self-equilibrium stress mode is carried out using a program called TCSELF (Amrita (2004) and Tan (2001)). Procedures of using the program are explained as follows.

2.1.4 Example of the input data

Input must be in the text format and the data were arranged in an order which enables the programme to read the information. The example of the input data format for the model shown in Figure 2.2 is given below;

```
9    18    0      (1st row)

1    0     0      0      0    0    0    (2nd row)
2    225   130    0      0    0    0
3    225   -130   0      0    0    0
4    100   0      15     0    0    0
5    175   43     15     0    0    0
6    175   -43    15     0    0    0
7    100   0      -15    0    0    0
8    175   43     -15    0    0    0
9    175   -43    -15    0    0    0

1    1     2      (11th row)
2    2     3
3    3     1
```

4	1	4
5	1	7
6	2	5
7	2	8
8	3	6
9	3	9
10	4	5
11	5	6
12	6	4
13	4	7
14	5	8
15	6	9
16	7	8
17	8	9
18	9	7

The first row corresponds to the total nodes, total members and number of external forces respectively. The second till tenth row represents joint coordinates and degrees of freedom. It is written in the following sequence: node number; x, y, z co-ordinate, degree of freedom in x, y, z direction (0: free, 1: fixed). The remaining rows represent the element connectivity. It corresponds to the member's number, node i, node j of the member, respectively.

2.1.5 Examples of output data

Example of the output data is shown as follows:

```
 nn is equal to     45

 select (gauss(1) / eigen(2))     1

 enter eps(in LU)     0.1

   *** r,q,p ***


     rank of equilibrium matrix *****   29

     statical indeterminancy ********    1

     rigid body displacement *******   16


 enter eps(in GAUSS)     0.1


 ***** normalized vectors ***


 1  0.3298708E+00    2  0.3319581E+00     3  0.3298708E+00     4 -0.2888190E+00

 5 -0.2888190E+00    6 -0.2897918E+00    7 -0.2897918E+00     8 -0.2897918E+00

 9 -0.2897918E+00   10 -0.1646188E+00  11 -0.1666138E+00  12 -0.1646188E+00

 13  0.4284354E-01   14  0.4284354E-01   15  0.4284354E-01   16 -0.1646188E+00

 17 -0.1666138E+00  18 -0.1646188E+00
```

From the output data, the degree of statically indeterminacy is 1. Hence q = 1, which implies that there is only one possible self-equilibrium stress mode. The row after the '***** normalized vectors ***' row shows the value of vector ***n*** as mentioned earlier which represents self-equilibrium stress mode. The arrangement of data corresponds to member's number and stress ratio respectively. The stress ratio's values contain information about different state of stress in the form of different sign which represents tension and compression states.

It is the responsibility of the analyst to determine which members should be in compression and tension. In cable dome structure, the tension elements will always represent the radial cable and inner ring and while compression members will represent the post and outer ring. So, the stress ratio data for the model shown in Figure 2.2 can be summarized as follows;

Table 2.1: Summary of the stress ratio data

Element's categories	**Range of members**
Outer ring (Compression ring)	1 - 3
Radial cable	4 - 9
Inner ring (Tension ring)	10 – 12, 16 - 18
Post	13 - 15

These ratios will be used to get the magnitude of stress applied on the structure to ensure that the structure maintains as a stable stand alone structure. Thus magnitude of stress to be provided will be determined from design consideration and material capacities used for the erection of dome.

2.2 Conceptualization and design

As mentioned before, cable-dome demonstrated structural efficiency in many long span roofs application. They are good choices for the construction of building which requires large free space such as multi-purpose hall, swimming pools, stadium and more. The shape of the dome can be simply in circular or elliptical form. Both shapes are technically impossible to be erected because curve members casting are costly and have to especially cast. Thus, polygon is used to approximate the circular and elliptical shape of the dome.

In this project, four types of model were designed and built to examine different configuration of the dome. It started with the assemblage of an even sided polygon dome with concentric opening. Then, it was proceeded to the assembly of a second mini dome with eccentric opening shifted in the direction of one of the structural axis and took an odd sided polygon as design shape. Lastly, assembly of a mini elliptical shape dome with even sided number and eccentric opening shifted in the direction of one of the structural axis of symmetry. Finally, a bigger size of the elliptical shape dome was built.

Configurations of the models which have been built are described below.

a) Mini model 1

This is a hexagonal shape model with concentric opening in the middle which is symmetrical with respect to x-axis and y-axis (Figure 2.3).

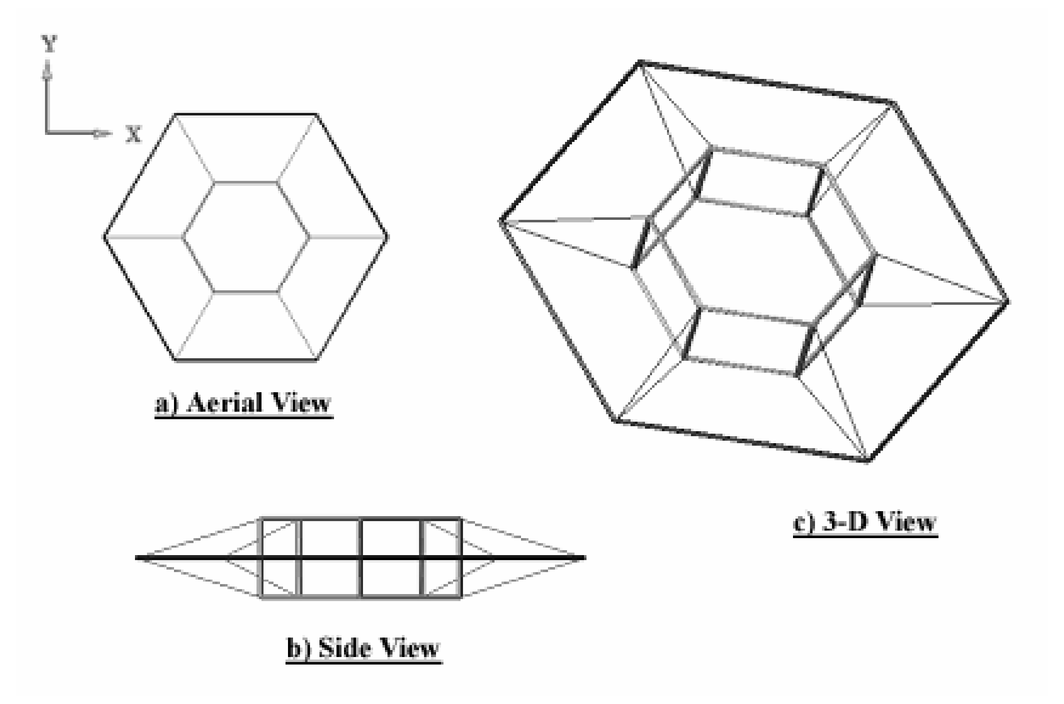


Figure 2.3: Hexagonal shape model

The dimension of the model by referring to Figure 2.4 is:

d_t = diameter of the tension ring = 108 mm

d_c = diameter of the compression ring = 280 mm

l_x = Shortest length between edges of the compression ring and the center of the tension ring = 140 mm

h = height of the upper tension ring

= height of the lower tension ring = 15 mm

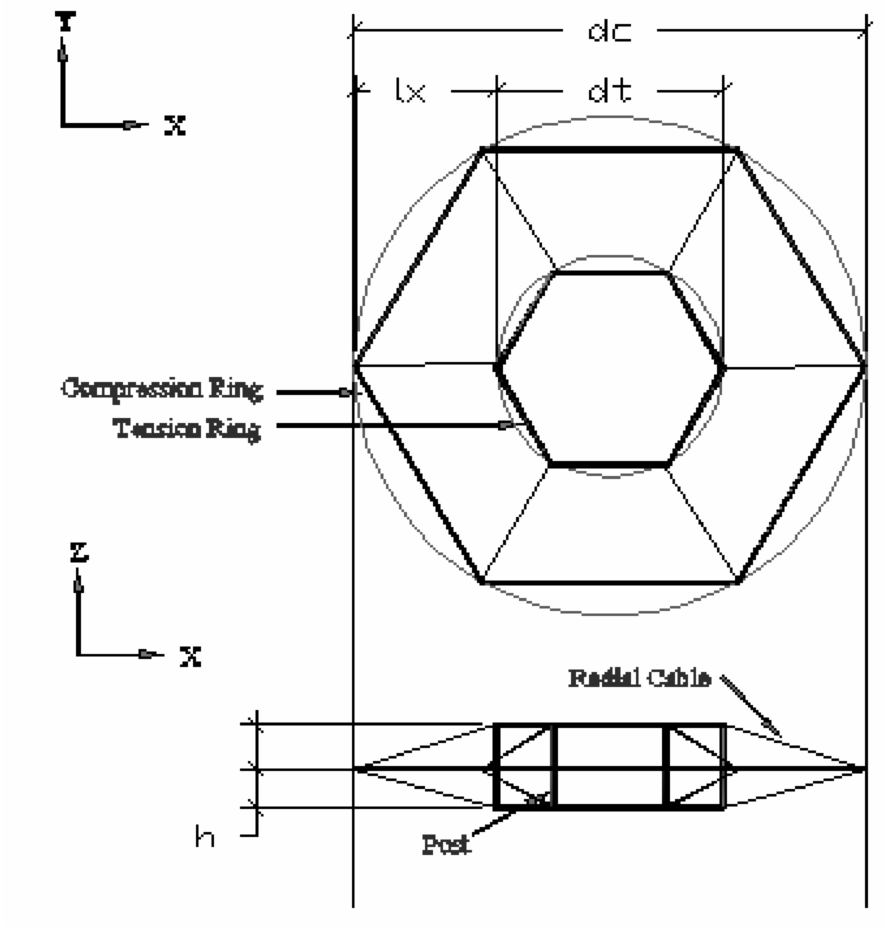


Figure 2.4: Description of symbol for hexagonal shape model

b) Mini model 2

This is a pentagonal shape model with eccentricity, e = 60 mm in the middle shifted in the direction of x-axis (Figure 2.5).

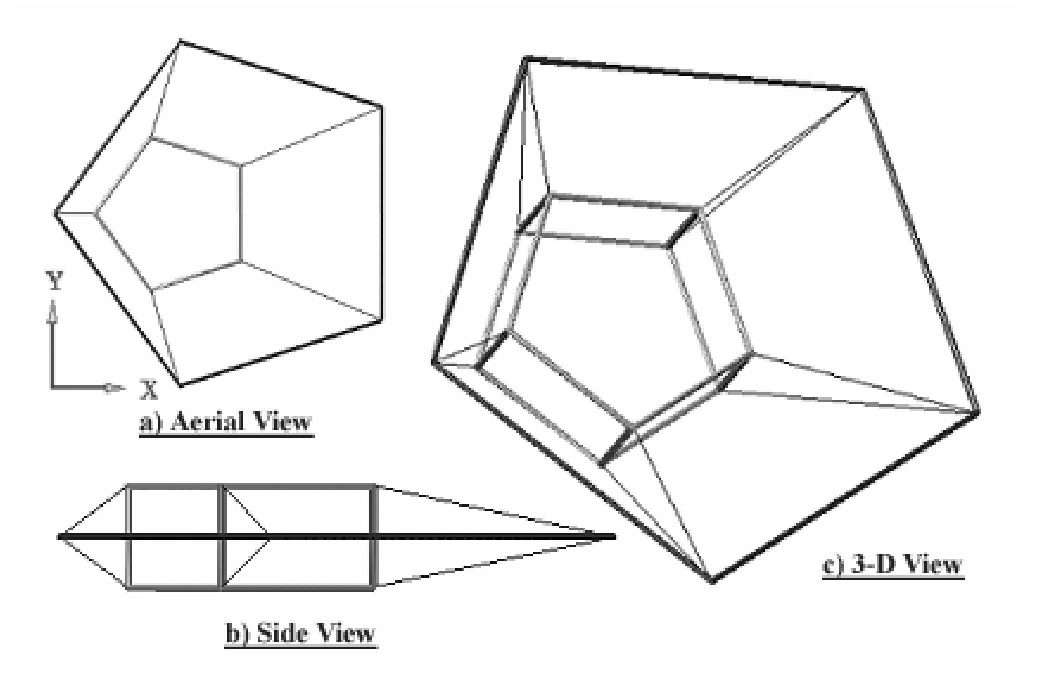


Figure 2.5: Pentagonal shape model

The dimension of the model by referring to Figure 2.6 is:

$\mathbf{d_t}$ = diameter of the tension ring = 108 mm

$\mathbf{d_c}$ = diameter of the compression ring = 280 mm

$\mathbf{l_x}$ **=** Shortest length between edges of the compression ring and the center of the tension ring = 60 mm

h = height of the upper tension ring
= height of the lower tension ring = 15 mm

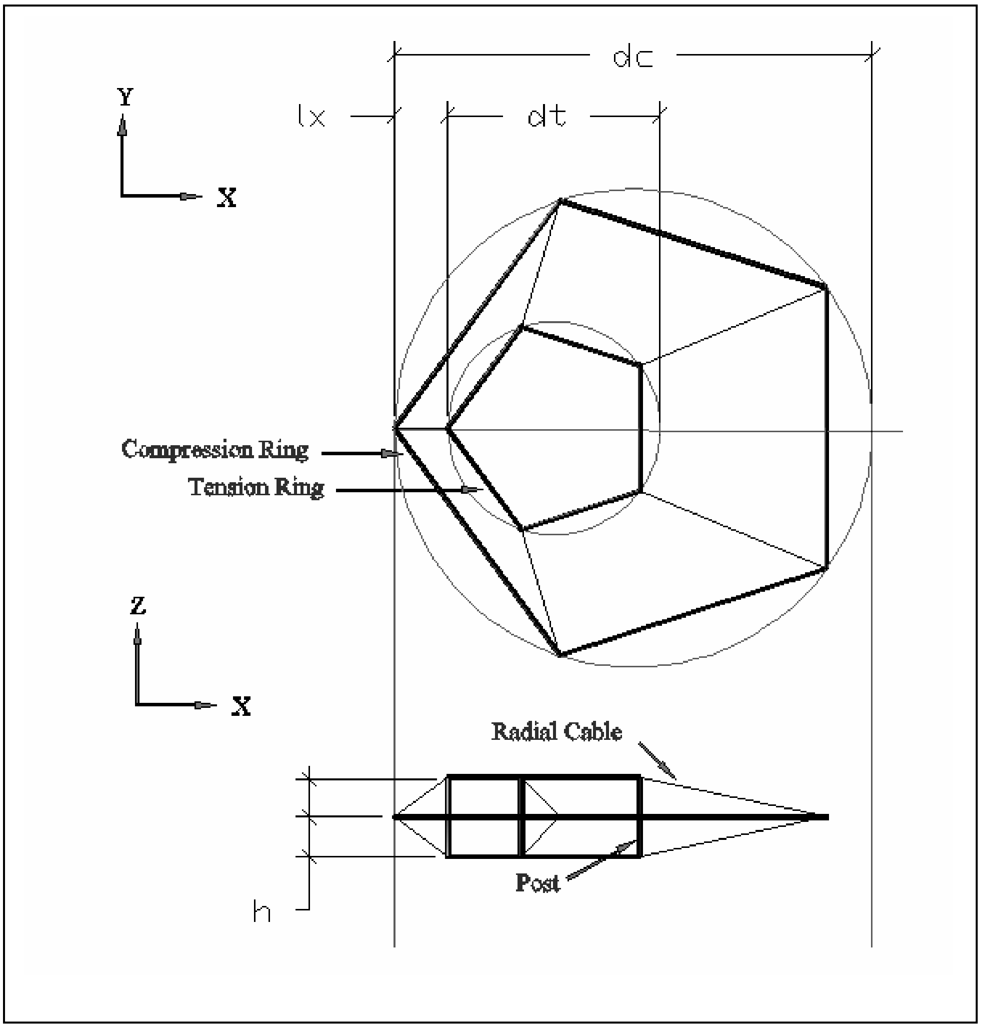


Figure 2.6: Description of symbol for pentagonal shape model

c) Mini model 3

This is an elliptical shape model with eccentricity, e = 50 mm in the middle shifted in the direction of x-axis. It consists of 16 sided members to generate an elliptical shape (Figure 2.7).

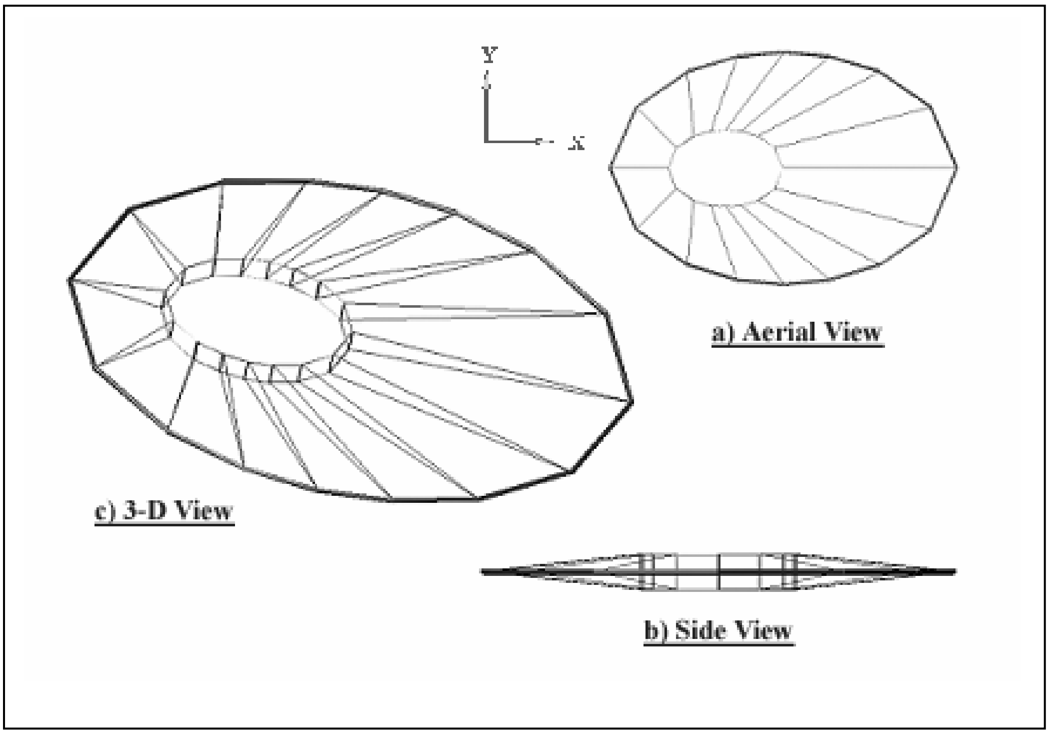


Figure 2.7: Elliptical shape model

The dimension of the model by referring to Figure 2.8 is:

p = Number of sides = 16

a_t = The longest diameter of the tension ring which is parallel with the x-axis = 100 mm

b_t = The shortest diameter of the tension ring which is parallel with the y-axis = 67 mm

a_c = The longest diameter of the compression ring which is parallel with the x-axis = 300 mm

$\mathbf{b_c}$ = The shortest diameter of the compression ring which is parallel with the y-axis = 200 mm

$\mathbf{l_x}$ = Shortest length between edges of the compression ring and the center of the tension ring = 50 mm

$\mathbf{h}$ = height of the upper and lower tension ring = 15 mm

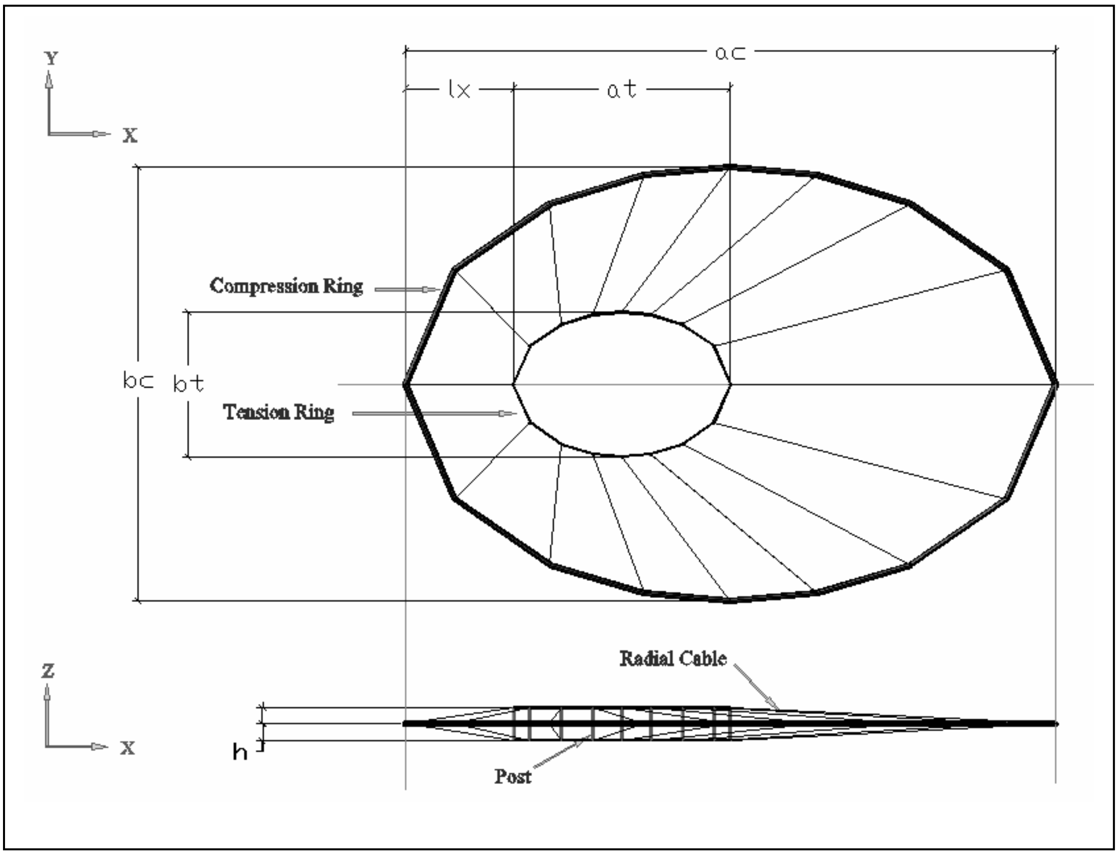


Figure 2.8: Description of symbol for elliptical shape model