CHAPTER ONE

GENERAL INTRODUCTION

1.1 Introductory Remarks:

The gross of construction industry requires developing of a structural system that can be used to provide a roof over an underlying area defined by general closed boundary line of arbitrary geometrical character. This unique system overcomes the arbitrary geometrical character problems while providing numerous advantages over the classical structural system [ALNigey 2011].

The thin shell concrete dome has become a very popular and affordable structure with wide variety of applications. Domes of this type have been constructed to store water, granular materials and fruit, even residential homes have been constructed with this double curved structure, in fact, the double curvature of the dome is where its efficiency is derived. One is able to maximize space within structure while minimizing the materials required building it. Unfortunatelyin the early years of its outset. the cost of building the form for a concrete dome easily doubled of the project, however, due to developments within the last few decades, it is now possible to avoid the intense formwork required, the new concept for structural forms involves the inflation of flexible membrane from often called (balloon), the air form is made out of such fabric as nylon and polyester in order to meet the requirement of durability, strength and shape in order to create the spherical shape of an air form, the dome roofs is apace structure that consists of truss or cable or truss and cable together. One of the famous types of domes roofs is stadia dome roofs[Robert 1994].

The stadia roof covers all of stadium or just audience seating place. The roofs covering area of audient seating place are classified based on roof geometry. Theform of this roof type classification with the seven roof types is illustrated in figure 1.1 and the seven roofs are:

1. Flat roof.
2. Flat roof with a sign board.
3. Flat roof with a back extension.
4. Flat elevated roof with aback extension.
5. Curved roof with an upward slope.
6. Straight roof with a downward slope.
7. Straight   roof with an upward slope.

1. Flat roof   2. Flat roof with a sign board.


3. Flat roof with a back extension   4.Flat elevated roof with aback extension

5. Curved roof with an upward slope. 6 .Straight roof with a downward slope.

7. Straight roof with an upward slope

Figure: 1.1 types of dome roofs (www.World Stadiums.com)

1.2 Research problem:

The use of dome roof maximizes space within structure while minimizing the material required for building. Due to cost concrete domes are replaced by steel space frames. But, as a result of joint type the behavior of the space frame is nonlinear. A study showing the benefits of nonlinear analysis of dome roofs enable the economic development of dome roof. This research presents a comparatives study between linear and nonlinear analysis of different types of dome roof.

1.3 Objectives of study:

This study aims to achieving the following objectives:

- To learn how the geometrically nonlinear finite element analysis of stadia domes roofs is developed.
- To study how to use computers in the linear and nonlinear analysis of the dome roofs.
- To investigate the need for nonlinear analysis of dome roofs.
- To apply Robot structure finite element program to obtain results for linear and nonlinear analysis of stadia dome roofs.
- To analyze and discuss the results obtained so as to draw conclusions and recommendations on the effect of nonlinearity.

1.4 Methodology of study:

1. Carrying out an extensive literature review referring to the following references or information recourses:
    - Finite element methods books, journals and research papers.
    - Inter net.
    - Finite element packages and application software manuals.
2. Presenting the nonlinear finite element two node straight 3D bar element which simulates stadia dome roofs as space trusses with three degrees of freedom per node.
3. Studying and presenting how ROBOT finite element package is used in the nonlinear analysis of stadia dome roofs.
4. Choice of practical examples of stadia dome roofs of known analysis results as case studies and carrying out their analysis using the program.
5. Analysis and discussion of results to draw conclusions and present recommendations.

1.5 Outlines of thesis:

This thesis consists of seven chapters; the contents of the chapters are as presented below:

- Chapter one covers the general introduction, research problem statement, objectives of study, methodology of study, and thesis outlines.

- Chapter two contains the literature review.

- Chapter three describes the linear and nonlinear formulation for space frameelement.

- Chapter four presents how AUTODESK ROBOT STRUCURAL ANALYSIS PROFESSINALprogram is linear and nonlinear analysis theory.

- Chapter five contains the applications of Robot finite element program, in the analysis of selected stadia dome roofs.

- Chapter six contains the analysis and discussions of the results.

- Chapter seven contains the conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Historical Background:

The stadia dome roof is one of the spatial structures which are composed of cables or bars. There are two types of this structure. The first is flexible structure. These types of structure have no stiffness and the shape of the structure is not determined when pre stress is not applied. The form of finding the process for the initial equilibrium is a significant problem for the flexible structure. The second is the rigid structure, for example the cable – truss stadia dome. Even if no pre stress is applied, the shape of this type of structure can be determined[ALNigey 2011].

As stated inArchpedia.com,9/7/05, "in the history of domes structures, four of the major influences due to: Anton Tedesko (1903-1994), who is attributed with much of the success of thin-shell structures in the U.S; Pier Luigi Nervi (1891-1979), who in Italy gave structural integrity to the complex curves and geometry of reinforced-concrete structures such as the Orbetello aircraft hangar (begun 1938) and Turin's exposition hall (1948-50); and the Spaniard Eduardo Torroja (1891-1961) and his pupil Felix Candela (1910-1997) who followed his lead. Essentially, each of the latter three attempted to create an umbrella roof the interior space of which could be subdivided as required, such as Torroja's grandstand for the Zarzuela racetrack in Madrid (1935). It also stated that "The Monolithic Dome can be attributed to David B. South (1939), president of the Monolithic Dome Institute, and his brothers – Barry and Randy South. They developed an efficient method for building a strong dome using a continuous spray-in-place process. In 1976, after years of planning and development they built the first Monolithic Dome in Shelley ".

2.2 Types of Space Trusses:

A space truss consists of members joined together at their ends to form a stable three - dimensional structures. The two mean types of grids and double layer grids.

According to Kumar and Kumar (2015)three dimensional frame works consisting of pin connected bars are called space trusses. They are characterized by hinged joints with no moments or torsional resistance. All members carry only axial compression or tension.Kumar and Kumar define "grid as two or more sets of parallel prismatic members intersecting each other at any angle and loaded by an external loading normal to the plane. They are characterized as two ways or three ways depending upon whether the members intersecting at a node run in two or three directions". Figure 2.1 shows different types of grids.

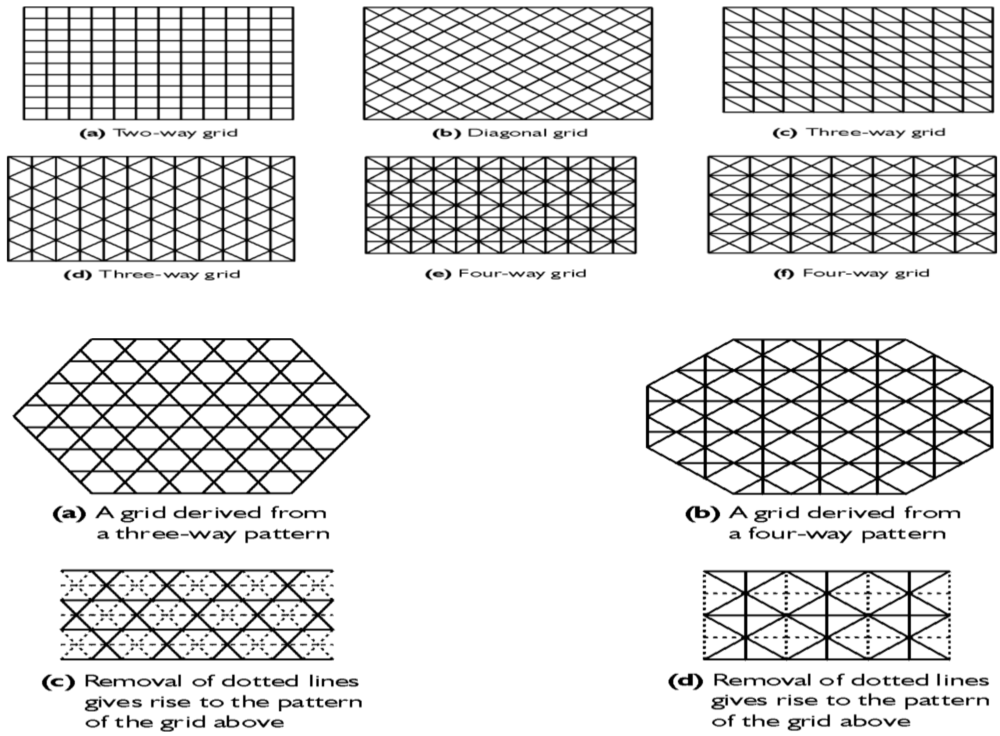


Figure 2.1: Examples of space grids(www.surrey .ac.uk /Eng. 23/2/2002).

They also state that: "space truss can be formed by two or three layers of grids. A double layer grid consists of two plane grids forming the top and bottom layers, parallel to each other and interconnected by vertical and diagonal members. A space truss is a combination of prefabricated tetrahedral, octahedral or skeleton pyramids or inverted pyramids having triangular, square or hexagonal basis with top and bottom members normally not lying in the same vertical plane. Double layer flat grid truss, having greater rigidity allow greater flexibility in layout and permit changes in the positioning of columns. Its high rigidity ensures that the deflections of the structures are within limits. They are usually built from simple prefabricated units of standard shape. Due to its high indeterminacy, buckling of any member under any concentrated load may not lead to the collapse of the entire structure". Examples of double layer grids are shown in figures 2.2 and 2.3.

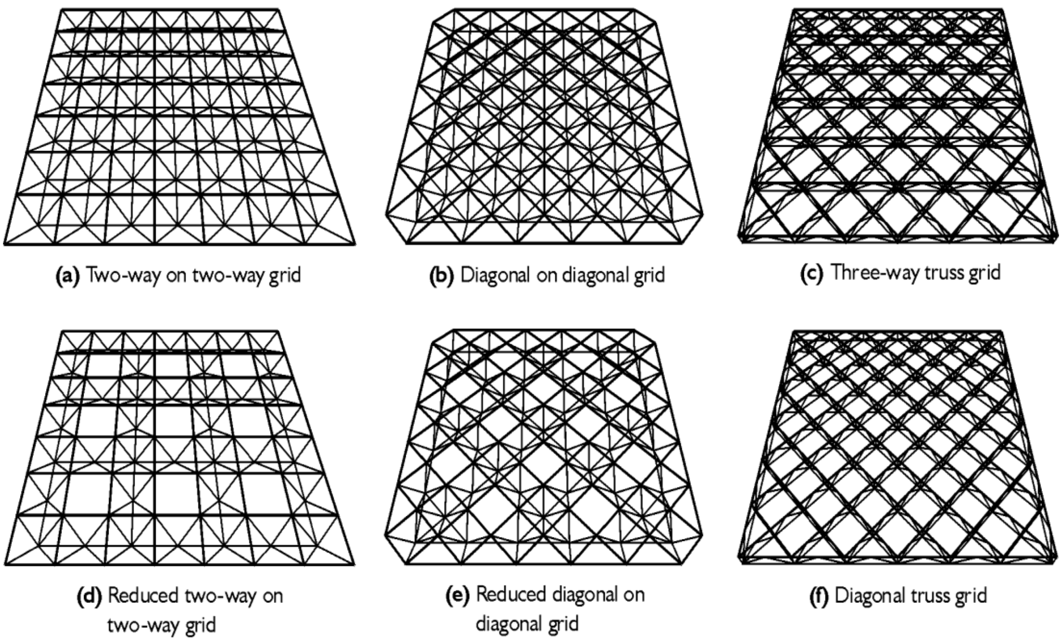


Figure 2.2: Examples of double layer(gridswww.surrey .ac.uk /Eng. 23/2/2002)

Figure 2.3: double layer grids (www.surrey .ac.uk /Eng. 23/2/2002)

As stated in www.surrey .ac.uk /Eng. 23/2/2002 domes are a structural system that consists of one or more layers of elements that are 'arched' in all directions. The surface of a dome may be a part of a single surface such as a sphere.

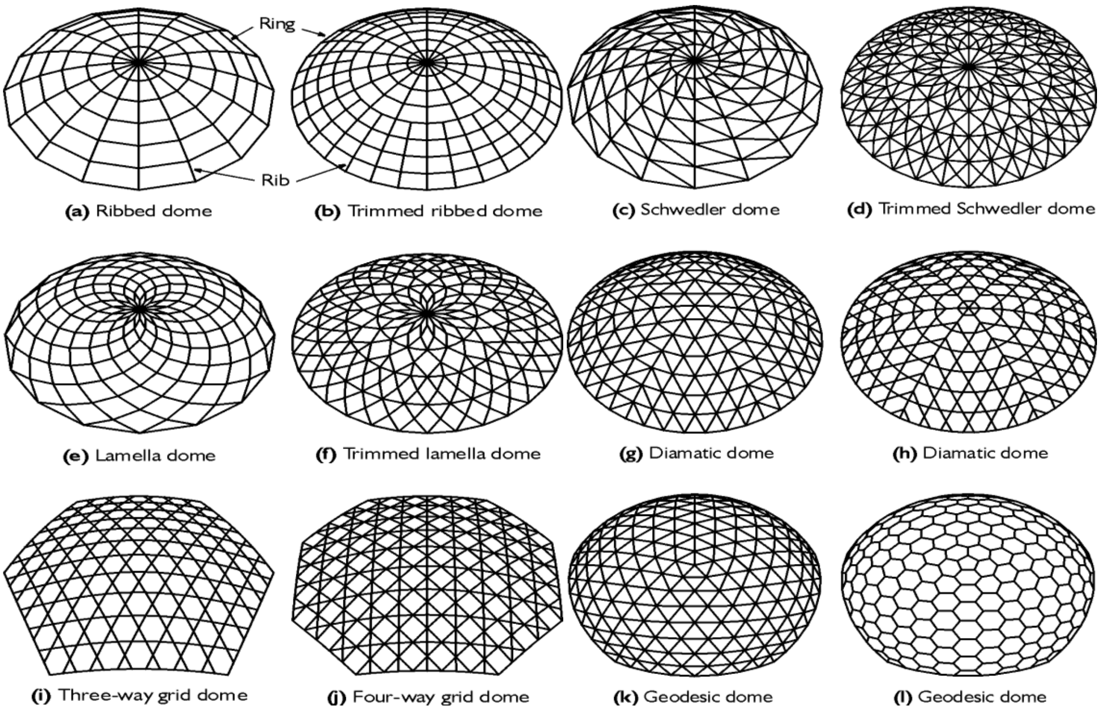


Figure 2.4: Examples domes (www.surrey .ac.uk /Eng. 23/2/2002).

Kumar and Kumaralso, list the advantages of space trusses as follows:

1. They are light, structurally efficient and use materials optimally. They can be designed in such a way that the total weight comes between 15 to 20kg/m^2.

2. They can be built up from simple, prefabricated units of standard size and shape. Hence they can be mass-produced in the factory, and can be easily and rapidly assembled at site using semi-skilled labor.

3. The small size components simplify the handling, transportation and erection.

4. They are elegant and economical means of covering large column free spaces.

5. They allow great flexibility in designing layout and positioning of end supports.

6. Services such as lighting, and air conditioning, can be integrated with space structures.

7. The use of complicated and expensive temporary supports during erection is eliminated.

2.3 Linear and Non-linear Analysis of Space Trusses:

In the review presented by Alnigey, 2011 it is statedthat "the statical behavior of the circular bar loaded in its plane has been one of the topics mostly studied. Obtained the flexibility matrix of a bar loaded in its plane was obtained by solving the set of the governing differential equations. Just gave the closed form of the element stiffness matrix of a thin circular bar of constant cross-section loaded in its plane was again given by solving the relevant set of differential equations. Alnigey,also, points out that utilizing castigliano'stheorem for the determination of the element stiffness matrix has been a commonly resorted to approach. And expressed The element stiffness matrices for a three dimensional circular bar by combining the element stiffness matrices obtained distinctly for each of the cases of loading either in or perpendicular to its plane.

Element stiffness matrices for planar bars have also been obtained in various ways by the finite element approach. Finding those element stiffness matrices which do not exhibit such negative effects as membrane and shear locking has meant that researchers have attempted to avoid this undesirable aspect. Among those gave the element stiffness matrix of a planar bar loaded in its plane on the basic of the Timoshenko beam theory. Other expressed in closed form the element stiffness matrix of rectangular planar bar taking into consideration both the axial and shear deformations.

In nonlinear finite element analysis, a major source of nonlinearities is due to the effect of large displacements on the overall geometric configuration of structure .Structures undergoing large displacements can have significant change in their geometry due to load induced deformations which can cause the structure to respond nonlinearly in a stiffening and a softening manner. This class of nonlinearities is known as geometric nonlinearities. Another important source of nonlinearities stems from the nonlinear relationship between the stress and strain which has been recognized in several behaviors. Several factors can cause the material behavior to be nonlinear. The dependency of the material stress – strain relation on the load history (as in plasticity problems), load duration (as in creep analysis), and temperature (as in thermo- plasticity) are some of these factors.This class of nonlinearities, can be idealized to simulate such effects which are pertinent to different application through of constitutive relations.

As presented by Belyschko, 1998 "Nonlinear finite element analysis is an essential component of computer- aided design. Testing of prototypes is increasingly being replaced by simulation with nonlinear finite element methods because this provides a more rapid and less expensive way to evaluate design concepts and design details. For example, in the field of automotive design, simulation of crashes is replacing full scale tests, both for the evaluation of early design concepts and details of the final design, such as accelerometer placement for airbag deployment, padding of the interior, and selection of materials and component cross-sections for meeting crashworthiness criteria. In many fields of manufacturing, simulation is speeding the design process by allowing simulation of processes such as sheet-metal forming, extrusion of parts, and casting. In the electronics industries, simulation is replacing drop-tests for the evaluation of product durability.

Temür et al, 2015, in their paper on nonlinear optimization, stated that"Particle swarm optimization (PSO) algorithm is a heuristic optimizationtechnique based on colony intelligence, developed through inspiration from socialbehaviors of birdflocks andfish schools. It is widely used in problems in which theoptimal value of an objective function is searched. Geometrically nonlinear analysisof trusses is a problem of this kind. The deflected shape of the truss where potentialenergy value is minimal is known to correspond to the stable equilibrium positionof the system analyzed. The results obtained show thatin case of using 20 or more particles, PSO produces very good and robust solutions. They concluded that The computations have shown that results with 20 and more particles match with those obtained by other methods. Additionally, it was seen that standard deviations of results with 20 and more particles is lower and more consistent in 100 independent analyses with each number of particles. Energy levels of results with 5 and 10 particles were determined to be greater than energy levels of results with other numbers of particles and by other methods. Besides, standard deviation values were also higher. Therefore, it is suggested that 20 or higher number of particles are to be used in analysis of truss structural systems by PSO method.

Salajegheh et al, 2009, proposed on efficient methodology to optimize space trusses considering geometric nonlinearity. They concluded that their last example results demonstrated the computational advantage of the suggested methodology for optimum design of geometrically nonlinear space trusses. Since the standard deviation value were large; for standardlopartid, they suggested that 20 or higher number of particles are to be used in analysis of truss structural.

Yang and Kou, 1994, presented a comprehensive text covering the theory and analysis of nonlinear framed structure; they divided the nonlinearities into two classes. The first class consists of material nonlinearity, which arises from changes in the physical response of material to stress and appears in the form of path-dependent and no unique constitutive laws. The second class consists of geometric nonlinearity, also referred to as the second order effects, which are produced by finite deformations coupled with change in stiffness of a structure under applied loading.

2.4 Summary:

The non-linear finite element analysis is very important to analyze space trusses because it enables the application of more loads to the space trusses for the same geometric and material properties. Thus, it results in economic solutions to space trusses. This research aims to confirm such benefit of nonlinear analysis of stadia dome roofs.

CHAPTER THREE

FORMULATION OF THE SPACE FRAME FINITE ELEMENT FOR LINEAR AND NONLINEAR ANALYSIS

3.1Introduction:

A frame element is formulated to model a straight bar of an arbitrary cross section, which can deform not only in the axial direction but also in the directions perpendicular to the axis of the bar. The bar is capable of carrying both axial and transverse forces, as well as moments. Therefore, a frame element is seen to possess the properties of both truss and beam elements.

The simplest way to approximate the curvature of the axis of a bar is to split it into a number of straight bar attached sequentially. In this case the element that must be formulated is the 3D straight bar element. The element has two nodes at ends. Each node has six degrees of freedom in local direction,and six degrees of freedom in the global direction.

3.2 Geometric definition of the element:

The geometric definitions of the element three are altogether six DOFs at a node in a 3D frame element: three translational displacements in the x, y and z directions, and three rotations with respect to the x, y and z axes. Therefore, for an element with two nodes, there are altogether twelve DOFs.

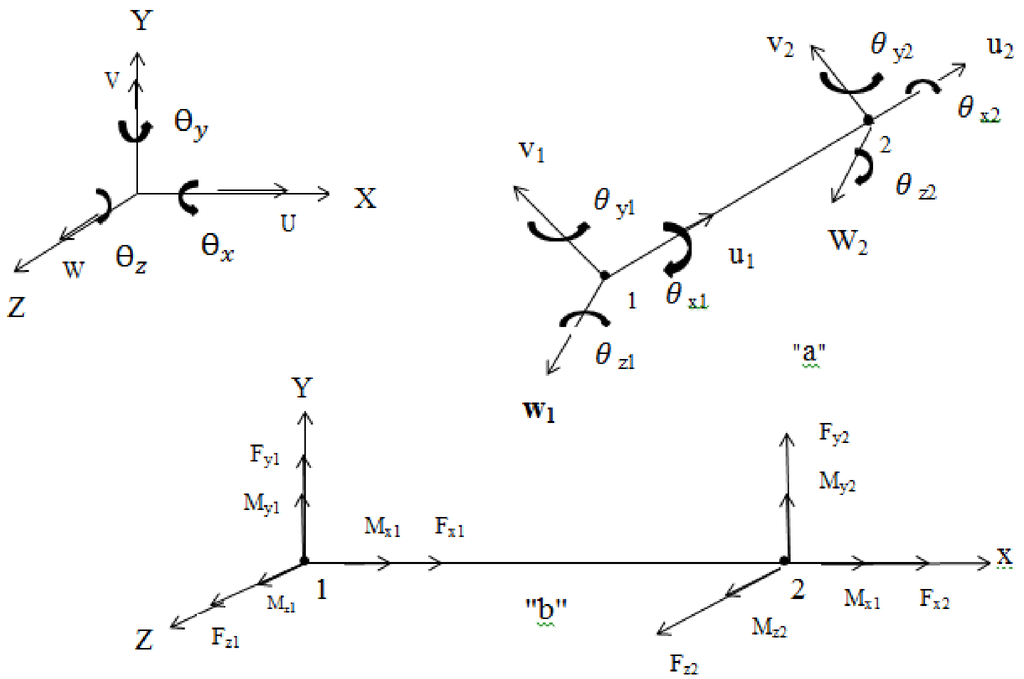


Figure (3.1) Space Frame : (a)Nodal degrees of freedom;

(b)Nodal forces and moments(Bin yang and Rongkou,1994)

3.3The displacement function:

The local coordinate:

The local displacement function of element can be written as follows:

$\{d\}= [N]\{d^{e}\}$ (3.1)

Where

{d}= displacement at any point.

[N]: the matrix of shape functions.

$\{d^e\}$: the vector of the local nodal displacements.

Equation (3.1) is written in explicit or as follows:

$u = N_1 u_1 + N_2 u_2$

$\theta_x = N_1 \theta_{x1} + N_2 \theta_{x2}$

$v = N_1' v_1 + N_1'' \theta_{z1} + N_2' v_2 + N_2'' \theta_{z2}$ (3.2)

$w = N_1' w_1 + N_1'' \theta_{y1} + N_2' v_2 + N_2'' \theta_{y2}$

Where the shape function are defined in terms of the local coordinate x as:

$$\{N\}^T = \{(1-\frac{x}{l}) \qquad \frac{x}{l}\}$$

$$\{N'\}^T=\{(1-3x^2/l^2+2x^3/l^3) \quad (3x^2/l^2-2x^3/l^3)\} \tag{3.3}$$

$$\{N''\}^T= \{(\frac{x}{l}-2x^2/l^2+x^3/l^3) \; (x^3/l^3-x^2/l^2)\}$$

And the vector of nodal displacements is:

$$\{d^e\} = \left\{ \begin{array}{c} u_1 \\ v_1 \\ w_1 \\ \theta_{x1} \\ \theta_{y1} \\ \theta_{z1} \\ u_2 \\ v_2 \\ w_2 \\ \theta_{x2} \\ \theta_{y2} \\ \theta_{z2} \end{array} \right\} \begin{array}{l} \left.\begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array}\right\} \text{displacement components at node 1} \\ \left.\begin{array}{c} \\ \\ \\ \\ \\ \\ \end{array}\right\} \text{displacement components at node 2} \end{array} \tag{3.4}$$

The local nodal displacement $\{d^e\}$ is defined in terms of the global nodal displacement $\{D^e\}$ as:

$$\{d^e\} = [T]\{D^e\} \tag{3.5}$$

where

$$\{D^e\} = \begin{Bmatrix} U_1 \\ V_1 \\ W_1 \\ \theta_{x1} \\ \theta_{y1} \\ \theta_{z1} \\ U_2 \\ V_2 \\ W_2 \\ \theta_{x2} \\ \theta_{y2} \\ \theta_{z2} \end{Bmatrix} \qquad (3.6)$$

and

$$[T] = \begin{bmatrix} [T_3] & 0 & 0 & 0 \\ 0 & [T_3] & 0 & 0 \\ 0 & 0 & [T_3] & 0 \\ 0 & 0 & 0 & [T_3] \end{bmatrix} \qquad (3.7)$$

[T] = the transformation matrix and its component $[T_3]$ is given by

$$[T_3] = \begin{bmatrix} l_x & m_x & n_x \\ l_y & m_y & n_y \\ l_z & m_z & n_z \end{bmatrix} \qquad (3.8)$$

where $l_k\, m_k\, n_k$ k= (x , y , z) are direction cosines:

l_x= cos (x , X), m_x = cos (x , Y), n_x= cos (x , Z)

l_y= cos (y , X), m_y = cos (y , Y), n_y= cos (y , Z) (3.9)

l_z= cos (z , X), m_z = cos (z , Y), n_z= cos (z , Z)

3.4The Strain:

The strain of any point within the element in local coordinates defined as:

$$\{\varepsilon\} = \begin{Bmatrix} \frac{du}{dx} \\ -\frac{d^2 w_0}{dx^2} \\ \frac{d^2 v_0}{dx^2} \\ -\frac{dw}{dx} \\ -\frac{dv}{dx} \\ -\frac{d\theta x}{dx} \end{Bmatrix} = [B]\,\{d^e\} \qquad (3.10)$$

Where [B] = the strain matrix.

In global coordinate the strain is:

$$\{\varepsilon\}=[B][T][D^e] \qquad (3.11)$$

$$\frac{dv}{dx} = \left(-\frac{6x}{l}+\frac{6x^2}{l^2}\right)v_1+\left(1-\frac{4x}{l}+\frac{3x^2}{l^2}\right)\theta_{z1}+\left(\frac{6x}{l}-\frac{6x^2}{l^2}\right)v_2+\left(\frac{3x^2}{l^2}-\frac{2x}{l}\right)\theta_{z2}$$

$$\frac{d^2 v_0}{dx^2} = \left(\frac{-6}{l}+\frac{12x}{l^2}\right)v_1+\left(-\frac{4}{l}+\frac{6x}{l^2}\right)\theta_{1}+\left(\frac{6}{l}-\frac{12x}{l^2}\right)v_2+\left(\frac{6x}{l^2}-\frac{2}{l}\right)\theta_{z2}$$

$$\frac{du}{dx} = \left(-\frac{1}{l}\right)u_1+\frac{1}{l}u_2$$

$$\frac{d\theta x}{dx} = \left(-\frac{1}{l}\right)\theta_{x1}+\frac{1}{l}\theta_{x2} \qquad (3.12)$$

$$\frac{d^2 w_0}{dx^2} = \left(\frac{-6}{l}+\frac{12x}{l^2}\right)w_1+\left(-\frac{4}{l}+\frac{6x}{l^2}\right)\theta_{y1}+\left(\frac{6}{l}-\frac{12x}{l^2}\right)w_2+\left(\frac{6x}{l^2}-\frac{2}{l}\right)\theta_{y2}$$

3.5The stress strain relation:

From the stress strain relation the stress is given in local coordinates by:

$$\{\sigma\} = [D]\,\{\varepsilon\} = [D]\,[B]\,\{d^e\} \qquad (3.13)$$

Where [D] the elasticity matrix

$$\{\ \sigma\ \} = \begin{Bmatrix} N_x \\ M_y \\ M_z \\ Q_y \\ Q_z \\ M_x \end{Bmatrix} \qquad (3.14)$$

In global coordinate the stress is:

$$\{\sigma\} = [D]\ [B]\ [T]\ [D_e] \qquad (3.15)$$

3.6Element stiffness matrix:

The stiffness matrix in local coordinates can be written as:

$$[k^e] = \int_{ve} [B]^T[D][B]dv^e \qquad (3.16)$$

The stiffness matrix $[k^e]$ for the space frame element, which has dimension of 12*12, can be defined as follows:

$$[k] = \begin{bmatrix} [k1] & [k2] \\ [k2] & [k3] \end{bmatrix} \qquad (3.17)$$

Where the sub matrices are

$$[k_1] = \begin{bmatrix} \frac{AE}{l} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EIz}{l^3} & 0 & 0 & 0 & \frac{6EIz}{l^2} \\ 0 & 0 & \frac{12EIy}{l^3} & 0 & -\frac{6EIz}{l^2} & 0 \\ 0 & 0 & 0 & \frac{GJ}{l} & 0 & 0 \\ 0 & 0 & \frac{6EIz}{l^2} & 0 & \frac{EIy}{l} & 0 \\ 0 & -\frac{6EIz}{l^2} & 0 & 0 & 0 & \frac{EIz}{l} \end{bmatrix} \qquad (3.18)$$

$$[k_2] = \begin{bmatrix} \frac{-AE}{l} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-12EIz}{l^3} & 0 & 0 & 0 & \frac{6EIz}{l^2} \\ 0 & 0 & \frac{-12EIy}{l^3} & 0 & -\frac{6EIz}{l^2} & 0 \\ 0 & 0 & 0 & -\frac{GJ}{l} & 0 & 0 \\ 0 & 0 & \frac{6EIz}{l^2} & 0 & \frac{2EIy}{l} & 0 \\ 0 & -\frac{6EIz}{l^2} & 0 & 0 & 0 & \frac{2EIz}{l} \end{bmatrix} \qquad (3.19)$$

$$[k_3] = \begin{bmatrix} \frac{AE}{l} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{12EIz}{l^3} & 0 & 0 & 0 & -\frac{6EIz}{l^2} \\ 0 & 0 & \frac{12EIy}{l^3} & 0 & \frac{6EIz}{l^2} & 0 \\ 0 & 0 & 0 & \frac{GJ}{l} & 0 & 0 \\ 0 & 0 & -\frac{6EIz}{l^2} & 0 & \frac{EIy}{l} & 0 \\ 0 & \frac{6EIz}{l^2} & 0 & 0 & 0 & \frac{EIz}{l} \end{bmatrix} \qquad (3.20)$$

The element stiffness matrix in global coordinateis :

$[K^e]=[T]^T [k^e][T]$ (3.21)

3.7Element nodal load vector:

The nodal load vector in local coordinate:

$\{F^e\}= \{F_b^e\} + \{F_s^e\} - \{F_{\sigma i}^e\} +\{F_{\varepsilon 0}^e\}$ (3.22)

Where:

The element nodal load vector due to body force $\{F_b^e\}$:

$\{F_b^e\} = \int_{ve} [N]^T\{b\}\, dv^e$ (3.23a)

The element nodal load vector due to surface force $\{F_s^e\}$:

$\{F_s^e\} = \int_{se} [N]^T\{t\}\, dA^e$ (3.23b)

The element nodal load vector due to initial strain $\{F^{e}_{\varepsilon_0}\}$:

$$\{F^{e}_{\varepsilon 0}\} = \int_{ve} [B]^T[D][\varepsilon_0]\, dv^e \qquad (3.23c)$$

The element nodal load vector due to initial stress $\{F^{e}_{\sigma i}\}$:

$$\{F^{e}_{\sigma i}\}=\int_{ve} [B]^T\{\sigma_i\}dv^e \qquad (3.23d)$$

The Element nodal load vector in global coordinates is:

$$\{F^{e}_{s}\}=\{T\}^T\{F^{e}_{1}\} \qquad (3.24)$$

The structure system load vector is $\{F_s\}=$

$$\sum_e\{F^{e}_{s}\} + \{Fc\} \qquad (3.25)$$

Where $\{F_c\}$ is the vector of concentrated nodal forces

The final structure system equation:

$$[K_s]\ \{D_s\}=\{F_s\} \qquad (3.26)$$

$$[K_s]=\sum_e[K^e] \qquad (3.27)$$

Where;

$[K_s]$= structure stiffness matrix.

$[K^e]$= element stiffness matrix.

$[F_s]$= structure global load vector.

3.8 3D Geometrically nonlinear thin space frame finite element formulation:

The formulation is a Total lagrangian formulation, based on Green strains. The formulation assumes small strain large rotation deformation. Since the element is thin, shear stresses are assumed to be negligible so that plane sections before deformation remain plane and normal to the beam axis after deformation. Also, the torsional curvature is assumed to be small, thus neglecting longitudinal warping of the x-section (Mohamed,1983).

3.9The Incremental Equilibrium Equations:

For the geometrically nonlinear two nodes, three dimensional frame element, Green strains, in local coordinates, at a general point are written as:

$$\{\varepsilon\} = \{\varepsilon_0^0\} + \{\varepsilon_0^l\} \tag{3.28}$$

Where $\{\varepsilon_0^0\}$, the infinitesimal strain is given by:

$$\{\varepsilon_0^0\} = \{\frac{du_0}{dx} \quad -\frac{d^2w_0}{dx^2}\frac{d^2v_0}{dx^2} \quad -\frac{dw_0}{dx} \quad -\frac{dv_0}{dx} \quad -\frac{d\theta_x}{dx}\}^T \tag{3.29}$$

$= [B_0]\{a_0\}$

$\{a_0\}$ being the vector of local nodal variables:

$$\{a_0\} = \{u_1 \ v_1 \ w_1 \theta_{x1} \theta_{y1} \ \theta_{z1} \ u_2 v_2 w_2 \ \theta_{x2} \ \theta_{y2} \theta_{z2}\}^T \tag{3.30}$$

The nonlinear strain$\{\varepsilon_0^l\}$ is written in terms of the displacement gradients as:

$$\{\varepsilon_0^l\} = \frac{1}{2}[B_L(a_0)]\{a_0\} = \frac{1}{2}[A_\Theta]\{\theta_0\} \tag{3.31}$$

In which

$$[A_\Theta] = \begin{bmatrix} \frac{du}{dx} & \frac{dv}{dx} & \frac{dw}{dx} & 0 & 0 & 0 & 0 \\ -\frac{d^2w}{dx^2} & 0 & -\frac{d^2u}{dx^2} & \frac{dw}{dx} & 0 & \frac{du}{dx} & 0 \\ -\frac{d^2v}{dx^2} & \frac{d^2u}{dx^2} & 0 & \frac{dv}{dx} & \frac{du}{dx} & 0 & 0 \\ \frac{dw}{dx} & 0 & \frac{du}{dx} & 0 & 0 & 0 & 0 \\ \frac{dv}{dx} & \frac{du}{dx} & 0 & 0 & 0 & 0 & 0 \\ -\frac{d\Theta_x}{dx} & \frac{d^2w}{dx^2} & \frac{d^2v}{dx^2} & 0 & \frac{dw}{dx} & \frac{-dv}{dx} & \frac{du}{dx} \end{bmatrix} \tag{3.32}$$

And

$$\{\theta_0\} = \{\frac{du_0}{dx}\ \frac{dv_0}{dx}\ \frac{dw_0}{dx}\ \frac{d^2u_0}{dx^2}\ -\frac{d^2v_0}{dx^2}\ -\frac{d^2w_0}{dx^2}\ -\frac{d\theta_x}{dx}\}^T$$

$$= [G_0]\{a_0\} \qquad (3.33)$$

Taking variations of the nonlinear strain with respect to the nodal variables, the strain displacement matrix is given by:

$$[B] = [B_0] + [B_L(a_0)] \qquad (3.34)$$

$$= [B_0] + [A_\Theta][G_0]$$

The vector of the stress resultants is:

$$\{s_0\} = [D]\{\varepsilon\}$$

$$= \{N_x \quad M_y \quad M_z \quad Q_y \quad Q_z \quad M_x\}^T \qquad (3.35)$$

Where:

N_x = axial force.

M_y, M_z = bending moments.

Q_y , Q_z = shear forces.

M_x = torsional moment.

The modulus matrix [D]is given in terms of young modulus E and modulus of rigidity G and x-section area and properties as:

$$[D] = \begin{bmatrix} EA & 0 & 0 & 0 & 0 & 0 \\ 0 & EIz & 0 & 0 & 0 & 0 \\ 0 & 0 & EI_y & 0 & 0 & 0 \\ 0 & 0 & 0 & k_yGA & 0 & 0 \\ 0 & 0 & 0 & 0 & k_zGA & 0 \\ 0 & 0 & 0 & 0 & 0 & G(k_zI_z + k_yI_y) \end{bmatrix} \qquad (3.36)$$

In which k_y and k_z are x-section shape shear factors.

The tangent stiffness matrix now takes the following form :

$$[K_T] = \int_{L0} [B]^T[D][B]\, dL_o + \int_{L0} [G_0]^T[P_{oi}][G_0]\, dL_o$$

$$= [K_0]+[k_L(a_0)]+[k_\sigma] \qquad (3.37)$$

In which $[P_{oi}]$ is the initial stress matrix which is defined in terms of the initial stress resultants as:

$$[P_{oi}] = \begin{bmatrix} [F_i] & [M_i] \\ [M_i]^T & [0] \end{bmatrix} \qquad (3.38)$$

$$\text{Where } [F_i] = \begin{bmatrix} N_i & Q_{zi} & Q_{yi} \\ Q_{zi} & N_i & 0 \\ Q_{yi} & 0 & N_i \end{bmatrix} \qquad (3.39)$$

$$\text{And } [M_i] = \begin{bmatrix} 0 & M_{zi} & M_{yi} & T_i \\ M_{zi} & 0 & -T_i & 0 \\ M_{yi} & T_i & 0 & 0 \end{bmatrix} \qquad (3.40)$$

CHAPTER FOUR
AUTODESK ROBOT STRUCURAL ANALYSIS PROFESSINAL NONLINEAR THEORY

4.1 Introduction:

Auto desk Robot as introduced by Microsoft, "structural analysis professional 2015" (referred to as Robot)is an integrated graphic program for modeling, analyzing and designing various types of structures it lets you create structures, carryout calculation and verify result, Robot nonlinear theory is based on updated lagrangian geometric nonlinearity. The theory also includes material nonlinearity which was not considered in this research.

4.2 Non-linear Static Analysis:

A non-linear analysis consists in the incremental application of loads. During the calculations, loads are not considered at a specific time, but they are gradually increased and solutions to successive equilibrium states are performed.

The non-linear behavior of a structure can be caused by a single structure element (structural or material non-linearity) or by a non-linear force-deformation relation in the whole structure (geometric non-linearity).

The following non-linear elements can cause a structural non-linearity:

- Compression / tension elements
- Cable elements
- Non-linear constraints (i.e. unilateral constraints or supports, releases, compatible nodes with the rigid parameter assigned).
- Material plasticity
- Non-linear hinges.

4.3Geometric non-linearity options:

The geometric non-linearity options take the actual higher-order effects into consideration and often improve the convergence of the calculation process for a structure including non-linear elements.

4.3.1 P-Delta analysis:

This analysis considers the second-order effects, such as changing the stiffness of the element under the influence of the stress state in the element. It also considers thegeneration of moments resulting from the action of vertical forces at thenode displaced horizontally.

4.3.2 Large displacements analysis:

This analysis considers third-order effects, such as the additional lateral rigidity and stresses resulting from deformation or rotation. This effect considers additional forces arising in a deformed structure such as a beam with fixed supports on both ends, loaded by a vertical load, longitudinal forces arise and the deflection decreases.

Two methods can be used to solve a system of non-linear equations: the Incremental method, and the Arc-length method.

4.4Analysis process:

Three algorithms are available to solve nonlinear problems:

- The Initial Stress method.-
- The Modified Newton-Raphson method.-
- The Full Newton-Raphson method.

In general, the Initial Stress method is the quickest one, and the Full Newton-Raphson method is the slowest. However, the probability of convergence is greater with the Full Newton-Raphson method than with the Initial Stress method

4.5Bar element in the non-linear analysis available in Robot:

4.5.1Preliminaryremarksandassumptions:

The following assumptions have been adopted for bar (frame) elements:

- Uniform formulation for 2D and 3D (2d & 3D frames, grillages).
- Uniform element allowing for material and/or geometrical non-linearity.
- Standard displacement degrees of freedom at 2 extreme nodes
  $d=\{u,\phi\}= [u_x , u_y , u_z , \phi_x,\phi_y,\phi_z]$ (4.1)

  Where:

U_x,U Displacement in x-direction.

U_y,V Displacement in y-direction.

U_z , W Displacement in z-direction.

ϕ , θrotation.

- Use of the following is allowed:

1-Shear deformation included (Timoshenko's model).

2-Tapered cross section -only for geometrical non-linearity.

3-Winkler's ground.

4-There are 2 levels of geometrical non-linearity available: P-Delta (second order theory), and Large displacements which is the most accurate theory possible with large displacements and rotations; this is an incremental approach with a geometry update.

- Assuming small displacements and absence of physical non-linearity for the limit, the results are identical as for standard linear elements.

- In the material non-linearity analysis the layered model and the constitutive stress-strain principle for the uniaxial stress-strain on the point (layer) level are applied.
- Shear and torsion states are treated as linearly elastic and have to be uncoupled from axial forces and bending moments on the cross section level.
- All types of element loads are allowable (identically as for standard elements). However, it is assumed that nodal forces acting on a structure are determined at the beginning of the process. The changes in the transfer of element loads onto nodes resulting from geometrical or material non-linearity are ignored.
- Apart from the elasto-plastic element, it is also possible to generate elasto-plastic hinges in selected bar cross sections as an extension of the "non-linear hinges.

4.5.2 Geometry, Kinematics and Strain Approximation:

Geometry, sign convention for forces, displacements, stresses and strains, is as shown in figure 4.1.

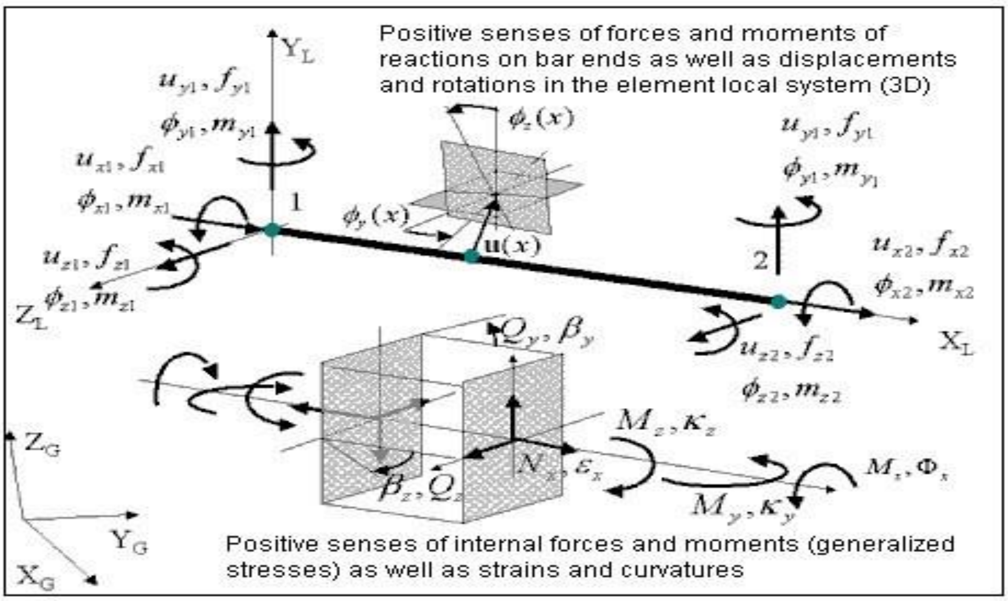


Figure 4.1 Basic kinematic relationships

In the element local system and in the geometrically linear range, the generalized strains E on the cross section level are as follow.

$E = \{ \varepsilon_{0x}, K_y, K_z, ß_y, ß_z, \psi \}^T$ (4.2)

where:

Axial strain in the bar axis	$\varepsilon_{0x} = \frac{du}{dx}$
Curvatures	$K_y = fy'x = \frac{\partial fy}{\partial x} = - \frac{d^2 w_0}{dx^2}$ $K_z = - f z'x = \frac{\partial fz}{\partial x} = - \frac{d2v}{dx2}$
Average angles (strain)	$ß_y = n'x - f z' = - \frac{dw}{dx}$ $ß_z = w'x - f y = - \frac{dv}{dx}$
Unit torsion angle	$\psi = f x'x = - \frac{d\theta x}{dx}$

4.5.3 Displacement approximation:

When there is a possibility to consider shear influence and consistence of results obtained for the linear element, physical shape functions considering shear influence have been implemented.

2D bars:

$$u(x) = Nu, \qquad N = \begin{bmatrix} h_1 & 0 & 0 & h_2 & 0 & 0 \\ 0 & h_3 & h_4 & 0 & h_5 & h_6 \\ 0 & h_3 & h_4 & 0 & h_5 & h_6 \\ \\ h_1 & 0 & 0 & h_3 & 0 & 0 \\ 0 & h_1 & h_8 & 0 & h_9 & h_{10} \\ 0 & h_1 & h_8 & 0 & h_9 & h_{10} \end{bmatrix} \qquad (4.3)$$

Shape functions and their derivatives are expressed by the formulas:

i	h_i	$h_{i,x}$
1	1- ξ	$-1/l$
2	ξ	$1/l$
3	$\frac{1}{l(1+2k)}[6\,\xi-6\,\xi^2]$	$\frac{1}{l^2(1+2k)}[6-12\,\xi]$
4	$\frac{1}{1+2k}[(1+2k)-2(2+k)\,\xi+3\,\xi^2]$	$\frac{1}{l(1+2k)}[-2(2+k)+6\,\xi]$
5	$\frac{1}{l(1+2k)}[-6\,\xi+6\,\xi^2]$	$\frac{1}{l^2(1+2k)}[-6+12\,\xi]$
6	$\frac{1}{(1+2k)}[-2(1-k)\,\xi+3\,\xi^3]$	$\frac{1}{l(1+2k)}[-2k-6\,\xi+6\,\xi^3]$
7	$\frac{1}{(1+2k)}[1+2k]$	$\frac{1}{l(1+2k)}[-2k-6\,\xi+6\,\xi^2]$
8	$\frac{l}{(1+2k)}[-(1+k)\,\xi+(2+k)\,\xi^2-\xi^3]$	$\frac{1}{(1+2k)}[-(1+k)+2(2+k)\,\xi-3\,\xi^3]$
9	$\frac{1}{(1+2k)}[2k\,\xi+3\,\xi^3-2\,\xi^3]$	$\frac{1}{l(1+2k)}[2k+6\,\xi-6\,\xi^2]$
10	$\frac{l}{(1+2k)}[k\xi+(1-k)\,\xi^2-\xi^3]$	$\frac{1}{(1+2k)}[k+2(1-k)\,\xi-3\,\xi^3]$

(4.4)

Same as in equation 3.2 and 3.3 with h_i=N_i and $\xi=\frac{x}{l}L^2$

$$K=\{\frac{6EI_Z}{K_Y GAL^2}, \frac{6EI_Y}{K_Z GAL^2}\}$$ for planes XY and XZ, respectively (4.5)

Kinematic relationships for the matrix notation (the geometrically lineartheory).

When considering the influence of imposed strains

$$E^0 = \{\varepsilon_0^{\Delta T}, K_Y^{\Delta T}, K_Z^{\Delta T}\}$$ (4.6)

Increment of generalized (sectional) strains:

$\Delta E=B_L \Delta U_{LOC}-\Delta E^0$

(4.7)

$\Delta U_{LOC}=T\Delta U_{GLO}$

2D:

$$E=\begin{bmatrix} \varepsilon_{0x} \\ K_Z \\ ß_Y \end{bmatrix} = \begin{bmatrix} h_{1,x} & 0 & 0 & h_{2,x} & 0 & 0 \\ 0 & -h_{3,x} & -h_{4,x} & 0 & -h_{5,x} & -h_{6,x} \\ 0 & h_3-h_{1,x} & h_4-h_{8,x} & 0 & h_5-h_{9,x} & h_6-h_{10,x} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (4.8)$$

3D:

$$E=\begin{bmatrix} \varepsilon_{0x} \\ K_y \\ K_Z \\ ß_y \\ ß_z \\ \phi \end{bmatrix} = \begin{bmatrix} h_{1,x} & 0 & 0 & 0 & 0 & 0 & h_{2,x} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & h_{3,x} & 0 & h_{4,x} & 0 & 0 & 0 & h_{5,x} & 0 & h_{6,x} & 0 \\ 0 & -h_{3,x} & 0 & 0 & 0 & -h_{4,x} & 0 & -h_{5,x} & 0 & 0 & 0 & -h_{6,x} \\ 0 & h_3-h_{1,x} & 0 & 0 & 0 & h_4-h_{8,x} & 0 & h_5-h_{9,x} & 0 & 0 & 0 & h_6-h_{10,x} \\ 0 & 0 & h_3+h_{1,x} & 0 & h_4+h_{8,x} & 0 & 0 & 0 & h_5-h_{9,x} & 0 & h_6-h_{10,x} & 0 \\ 0 & 0 & 0 & h_{1,x} & 0 & 0 & 0 & 0 & 0 & h_{2,x} & 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (4.9)$$

here:

$$u=\{u_1,u_2\}= \begin{cases} 2D: \{u_{x1},u_{y1},\phi_{z1}, u_{x2},u_{y2},\phi_{z2}\}^T \\ 3D: \{ u_{x1},u_{y1},u_{z1}, \phi_{x1}, \phi_{y1}, \phi_{z1},u_{x2},u_{y2}, u_{z2},\phi_{x2},\phi_{y2}, \phi_{z2}\}^T \end{cases}$$

(4.10)

4.5.4Strains at a point (layer)

Given the generalized strains {ε_{0x}, k_y , k_x } of a cross section, the e xl strain or its increment De xl at any point of the cross section l - of the coordinates yl, zl, is calculated as

$$\varepsilon_{xi}=\varepsilon_{0x}+k_y z_i+k_z y_i \quad (4.11)$$

$\varepsilon_{xi}=V_L^T E$; $V=\{1,z_i,y_i\}^T$

Finally, strain increment in the layer:E^0

$$\varepsilon_{xi}=V_L^T(\Delta E-\Delta E^0)=V_L^T(B\Delta u-\Delta E^0) \quad (4.12)$$

4.5.5 Stresses and internal forces within an element:

The constitutive principle on the point level.

The principle is adopted in the general incremental form, where current stresses σ_x^{n+1} are defined as a function of stress for the last equilibrium σ_x^n and current strain increment with imposed (thermal) strains considered,

$$\sigma_{xi}^{n+1} = F(\sigma_{xi}^{n+1}, \Delta\varepsilon_{xi}) \qquad (4.13)$$

Based on the function σ = f(ε) which describes the relationship in the process of active loading and on the specification of the principle of unloading and reloading. In particular, it may be the elastic-plastic principle with linear hardening and the specified principle of unloading, such as (a) elastic, (b) plastic, (c) damage, (d) mixed. For elastic unloading the passive and active process is performed along the same path σ = f(ε). For the remaining ones, it is performed along the straight line determined by the beginning point of a given unloading process {ε UNL, σ UNL } and the unloading module D UNL defined as

$$\text{(b)}: D_{unl\_p}=E; \quad \text{(c)} D_{unl\_D}=\frac{\sigma^n}{\varepsilon^n - e^n}; \quad \text{(d)} D_{unl\_m}=(1-a)D_{unl\_p}+aD_{unl\_D} \qquad (4.14)$$

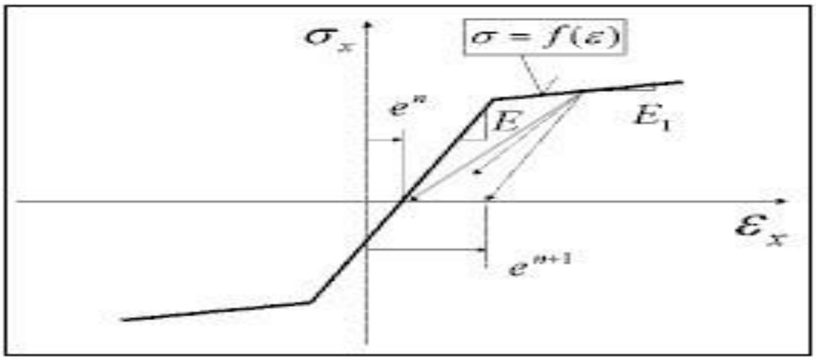


Figure (4.2) Stresses and internal forces within an element

e n is a memorized strain, for which the current active process has started, commenced after exceeding 0 by stresses with the unloading (e 1 = 0) assumed.

For the analysis it is necessary to provide the current stiffness assumed to be a derivative

$$D_x=\frac{\partial \sigma}{\partial \varepsilon} \tag{4.15}$$

Calculation of forces and cross section stiffness values.

On the cross-section level, the vector of internal forces (stress resultants) is composed of: N_x

(2D): $\sum = \{N_x, M_y, Q_z\}^T$

(3D) : $\sum = \{N_x, M_y, M_z, Q_y, Q_{z,} M_x \}^T$ (4.16)

States of shear and torsion ΣST are treated as linearly elastic and not conjugated with the state of axial/bending forces on the cross section level.

$Q_y^{n+1}=Q_y^n+k_y GA.\Delta ß_y$

$Q_z^{n+1} = Q_n^n+k_z GA.\Delta ß_z$ (4.17)

$M_x^{n+1}=M_x^n+GI_x.\Delta \phi$

Compression/tension states Σ NM are generally treated as conjugate when applying the layered approach. However, as long as the elastic state is guaranteed, i.e. until the current generalized strains fulfill the following elastic state condition:

$$\left|\frac{\varepsilon_{0x}}{\varepsilon_{ox\,ELA}}\right| + \left|\frac{K_Y}{K_{Y\,ELA}}\right| + \left|\frac{K_Z}{K_{ZELA}}\right| \leq 1 \tag{4.18}$$

where:

$\varepsilon_{ox\,ELA} = \; {}_{L}^{MIN}(f_{dl}/E_L)$;$K_{Y\,ELA}= \; {}_{L}^{MIN}(f_{dl}/(E_L Z_L)$;$K_{Z\,ELA}= \; {}_{L}^{MIN}(f_{dl}/(E_L Y_L)$; (4.19)

The cross section is treated as elastic and the layered approach is not activated.

$N_x^{n+1}=N_x^n+EA.\Delta\varepsilon_0$

$M_y^{n+1}=M_y^n+EI_y.\Delta k_y$ (4.20)

$M_z^{n+1}=M_z^n+EI_z.\Delta k_z$

Once violation of the elastic state condition is asserted,

Stresses induced by axial strains and bending are calculated separately for each layer and on their basis sectional quantities are calculated.

$N_x^{n+1}=\sum_{i-1}^{Nlayer} \sigma_{xi}^{n+1} A_i$

$M_y^{n+1}=\sum_{i-1}^{Nlayer} \sigma_{xi}^{n+1} A_i z_i \Longrightarrow \sum_{NM} = \begin{matrix} N \\ M_y \\ M_z \end{matrix} = \sum_{i-1}^{Nlayer} v_i \ \sigma_i \ A_i$ (4.21)

$M_z^{n+1}=\sum_{i-1}^{Nlayer} \sigma_{xi}^{n+1} Aiyi$

Stiffness on the level of D cross section is calculated as follows:

in the elastic state as:

D = diag {EA, EI_y, EI_z, K_yGA, k_zGA, GI_x}

After exceeding the elastic state condition as:

$$D=\begin{bmatrix} D_{NM} & 0 \\ 0 & D_{ST} \end{bmatrix} \quad (4.22)$$

Where:

$$D_{NM}=\sum_{i-1}^{Nlayer} DiAiVi \cdot v_L^T = \sum_{i-1}^{Nlayer} DiAi \begin{bmatrix} 1 & z_i & y_i \\ z_i & z_i^2 & y_i z_i \\ y_i & y_i z_i & y_1^2 \end{bmatrix} \quad (4.23)$$

D_{ST}=diag{K_yGA, K_zGA ,GI_X }

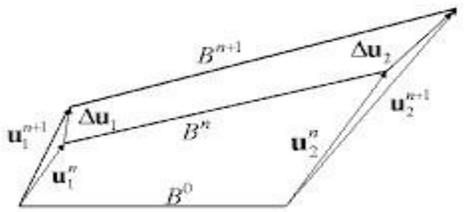
Nodal force vector and element stiffness matrix They are calculated by means of the standard formulas applying Gauss quadrature.

$$\mathbf{f} = \int_0^L \mathbf{B}^T \boldsymbol{\Sigma} dx = \sum_{iG=1}^{NGAUSS} \mathbf{B}^T (x_{iG}) \boldsymbol{\Sigma}_{iG} W_{iG} dJ_{iG}$$

$$\mathbf{K}^e = \int_0^L \mathbf{B}^T \mathbf{D} \mathbf{B} dx = \sum_{iG=1}^{NGAUSS} \mathbf{B}^T (x_{iG}) \mathbf{D}_{iG} \mathbf{B}(x_{iG}) W_{iG} dJ_{iG} \quad (4.24)$$

4.6. Geometrical Nonlinearity:

the following configurations are taken into consideration:



B0 - initial configuration

Bn - reference configuration (the last one for which equilibrium conditions are satisfied)

Bn+1 - current configuration (iterated).

An entry point for the element formulation is the virtual work principle saved in the following form for displacement increments:

$$\int \tau_{ij}{}^n \delta\Delta\eta_{ij} dV + \int_V C_{ijkl} \Delta\varepsilon_{kl} \delta\Delta\varepsilon_{ij} dV = F^{n+1} - \int_V \tau_{ij}{}^n \delta\Delta e_{ij} dV, \quad \forall \delta u \quad (4.25)$$

where:

Δε strain increment while moving Bn to Bn+1, Δe, Δηconstitute its parts, correspondingly: linear and non-linear with respect to the displacement increment Δu, whereas τ is a stress referring to the reference configuration and Cijkl is a tensor of tangential elasticity modules.

4.6.1The Non-linearity option:

it corresponds to the non-linear formulation, or the second order theory. Since material non-linearity is possible, the incremental formulation is being introduced (however, without modification of element geometry).

4.6.2Kinematic relations:

Strain increments in the matrix notation:

$\Delta E = \Delta e + \Delta\eta = B\Delta u_{loc} + 0.5 g^T H_N g$

(4.26)

Where:

$g = \{u_{,x}, v_{,x}, w_{,x}, \phi_{x,x}, \phi_{y,x}, \phi_{z,x}\}^T$

(4.27)

then the displacement increment gradient $g = \Gamma\Delta u$

$\Gamma = N_{,x}$ (4.28)

Whereas

$$H_N = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} (2D) \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} (3D)$$

is a selection matrix.(4.29)

Nodal force vector and element stiffness matrix

$$\mathbf{K}_{Loc} = \mathbf{K}_L + \mathbf{K}_\sigma$$

$$\mathbf{f}^{n+1} = \mathbf{f}^{n+1}_{ext} - \int \mathbf{B}^T \boldsymbol{\Sigma}^{n+1} dx - \mathbf{K}_\sigma^{n+1} \mathbf{u}^{n+1} = \mathbf{f}^{n+1}_{ext} - \mathbf{f}^{n+1}_{intL} - \mathbf{f}^{n+1}_{intNL}$$

$$\mathbf{K}_L = \int_0^L \mathbf{B}^T \mathbf{D} \mathbf{B} dx$$

$$\mathbf{K}_s = \int_0^L \mathbf{\Gamma}^T (N\mathbf{H}_N) \mathbf{\Gamma} dx$$

(4.30)

4.6.3Algorithm on the element level:

the element geometry is not modified; the local-global transformation is performed with the use of initial transformation matrix ${}^0\mathbf{T}$

$$\begin{aligned}
&\Delta\mathbf{u}_{Loc} = {}^0\mathbf{T}\Delta\mathbf{u}_{Glo},\\
&\Delta\mathrm{E} = \mathrm{B}\Delta\mathbf{u}_{Loc} + 1/2\mathbf{g}^T\mathbf{H}\mathbf{g} - \Delta\mathrm{E}^0\\
&\boldsymbol{\Sigma}^{n+1} = \boldsymbol{\Sigma}^{n+1}(\boldsymbol{\Sigma}^n, \Delta\mathrm{E}),\\
&\mathrm{K}_\sigma = \mathrm{K}_\sigma(\boldsymbol{\Sigma}^{n+1}),\\
&\mathbf{f}^{n+1}{}_{Loc} = \mathbf{f}^{n+1}{}_{ext} - \mathbf{f}^{n+1}{}_{int\,L} - \mathbf{f}^{n+1}{}_{int\,NL}\\
&\mathbf{f}_{Glo} = {}^0\mathbf{T}^T\mathbf{f}_{Loc}\\
&\mathrm{K}_{Loc} = \mathrm{K}_L + \mathrm{K}_\sigma\\
&\mathrm{K}_{Glo} = {}^0\mathbf{T}^T\mathrm{K}_{Loc}\,{}^0\mathbf{T}
\end{aligned} \tag{4.31}$$

4.6.4Large displacement option:

It is a certain variant of bar description allowing for large displacements. The approach of the updated Lagrange description is applied here.

Nodal force vector and element stiffness matrix

$$\begin{aligned}
&\mathrm{K}_{Loc} = \mathrm{K}_L + \mathrm{K}_\sigma\\
&\mathbf{f}^{n+1} = \mathbf{f}^{n+1}{}_{ext} - \int \mathbf{B}^T\boldsymbol{\Sigma}^{n+1}dx = \mathbf{f}^{n+1}{}_{ext} - \mathbf{f}^{n+1}{}_{int}\\
&\mathrm{K}_L = \int_0^{L^0}\mathrm{B}^T\mathrm{D}\mathrm{B}dx\\
&\mathrm{K}_s = \int_0^{L^0}\Gamma^T(\underline{\boldsymbol{\Sigma}}^{n+1})\Gamma dx\\
&\underline{\boldsymbol{\Sigma}} = \begin{bmatrix} N & M_y & 0\\ M_y & N & 0\\ 0 & 0 & 0\end{bmatrix}(2D),\quad \underline{\boldsymbol{\Sigma}} = \begin{bmatrix} N & M_y & M_z & 0\,0\,0\\ M_y & N & 0 & 0\,0\,0\\ M_z & 0 & N & 0\,0\,0\\ 0 & 0 & 0 & 0\,0\,0\\ 0 & 0 & 0 & 0\,0\,0\\ 0 & 0 & 0 & 0\,0\,0\end{bmatrix}(3D)
\end{aligned} \tag{4.32}$$

CHAPTER FIVE

RESULTS OF THE ANALYSES OF STADIA DOME ROOFS

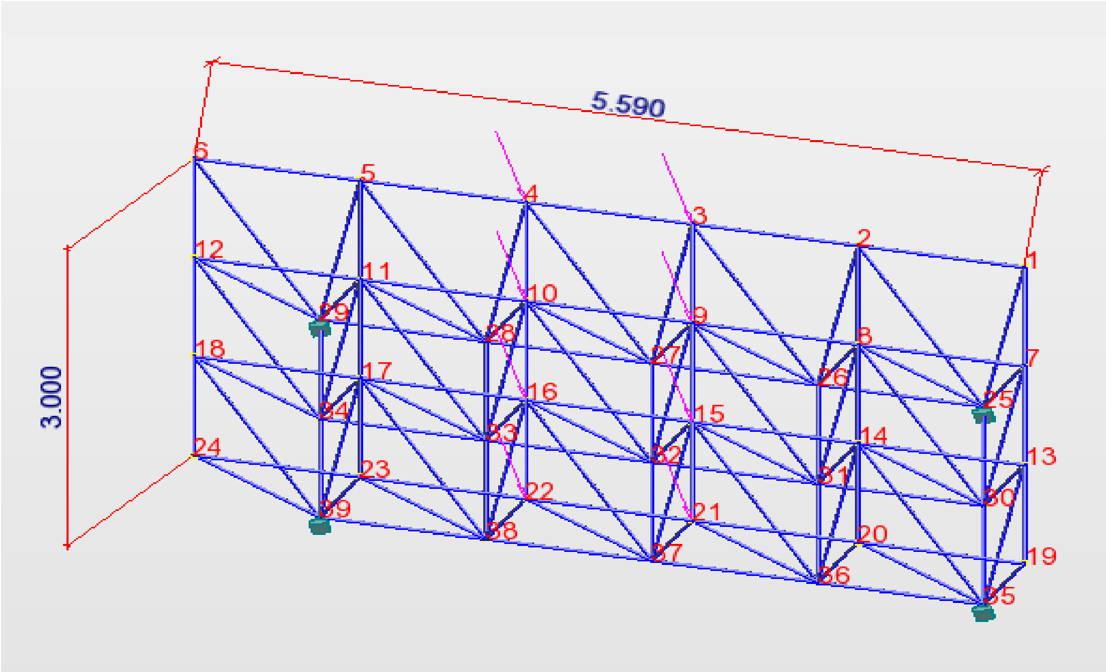
5.1 Introduction:

The geometrically nonlinear theory presented in Chapter Three was verified using the linear and nonlinear version of AutodeskRobot structure 2015 finite element program. This was done by carrying out linear and nonlinear analysis of four cases of dome roofs.

The four domes which cover the famous types of stadia roofs were selected as follows:

1- Ascending roof towards the field
2- Curved roof.
3- Star dome roof.
4- Circular dome roof.

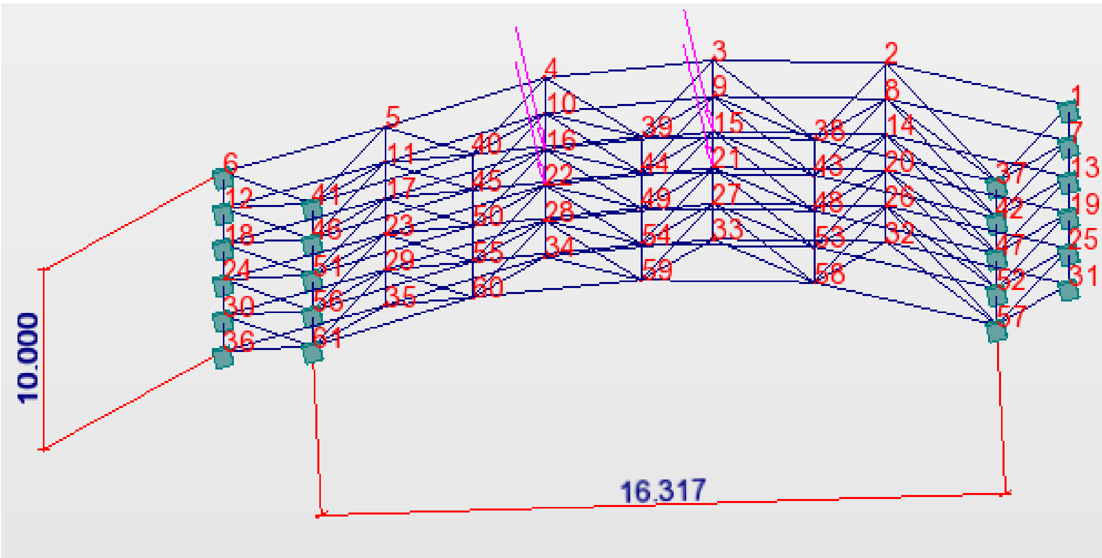
The roofs geometry with load data and support conditions are shown in figures (5.1) to (5.4).



Diameter= 28.284mm

$E=205kN /mm^2$

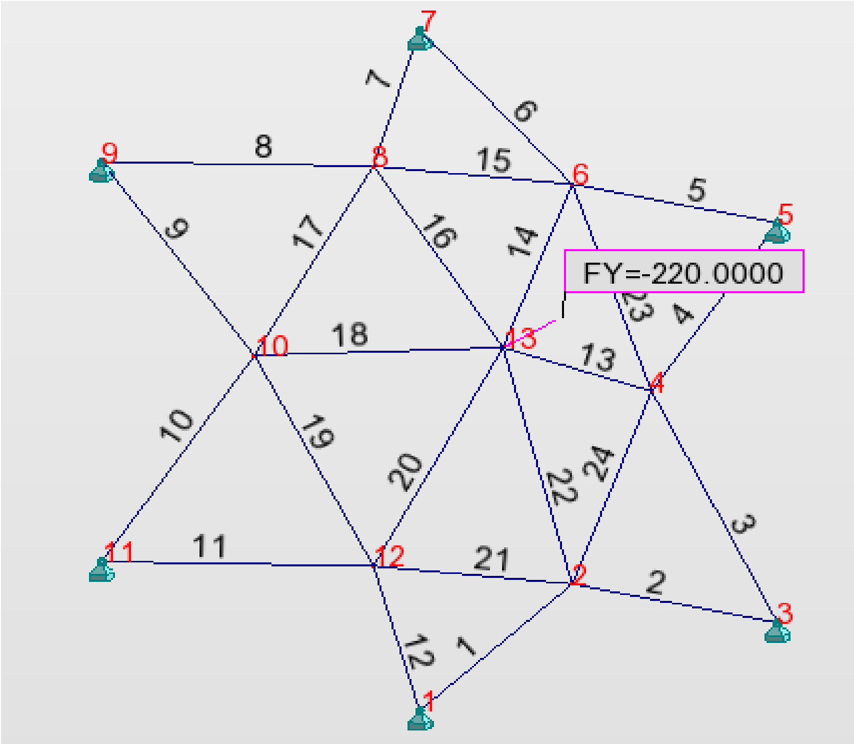
Fig (5.1) Ascending roof towards the field



Diameter= 63.83mm

$E=205kN /mm^2$

Fig (5.2) Curved roof



Diameter= 63. 83mm

E=205kN /mm^2

Fig (5.3.1) Star dome roof (Original)

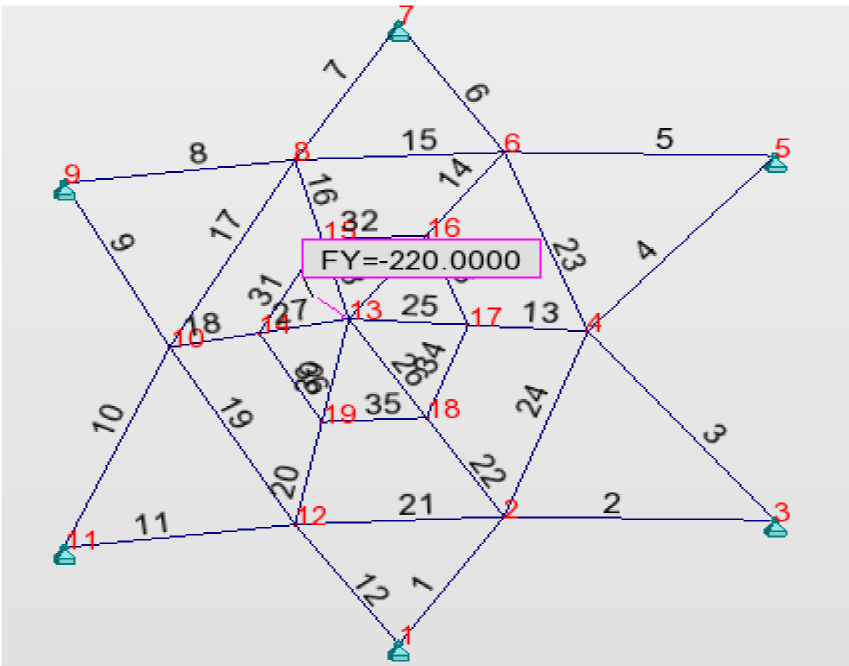


Fig (5.3b) Star dome roof (modified 1)

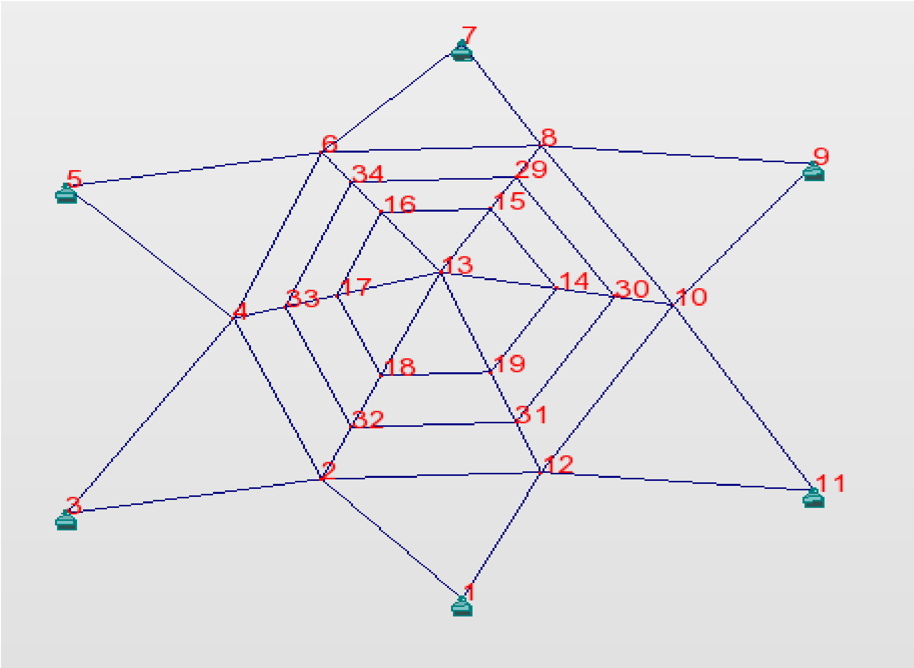
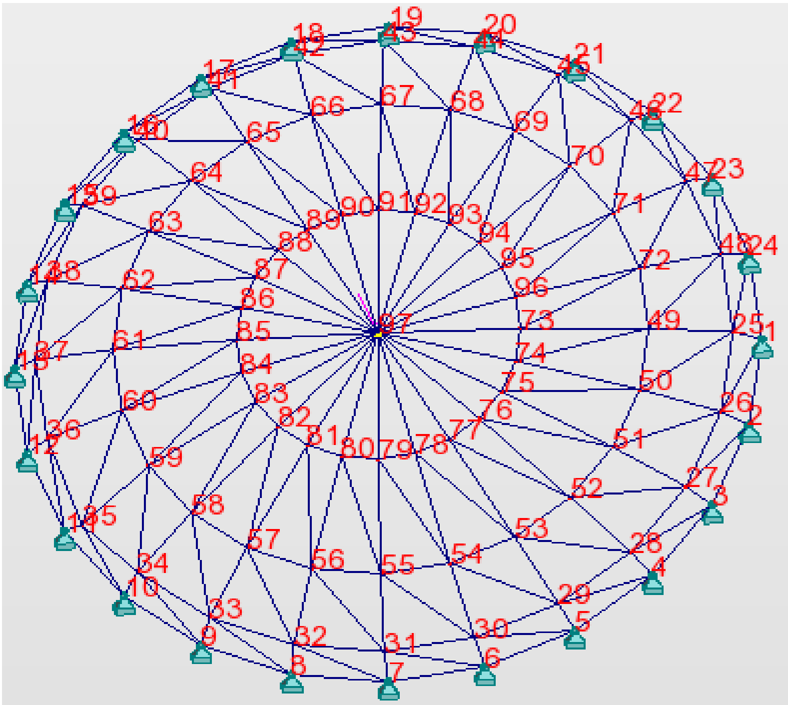


Fig (5.3c) Star dome roof (modified 2)



Diameter= 63. 83mm

E=205kN /mm^2

Fig (5.4) Circular dome roof

5.2 Ascending roof towards the field:

The ascending roof towards the field was represented by a finite model with 39 nodes and 120 elements with pin - jointed supports. The geometry, materials properties and loading are shown in fig (5-1). Autodesk Robot structure 2015 was used to carry out the linear and non-linear analysis. The results obtained for maximum vertical displacement, reaction and element force due to vertical load are shown and compared in tables (5-1a) , (5-1b) and (5-1c) respectively.

The load was applied in 11 increments, each of 10kN for linear and nonlinear analysis. 10iteralions were required for convergence with in each increment for nonlinear.

Table (5-1a): Vertical linear and nonlinear displacement for ascending roof

Load(kN)	Linear displacement(mm) Node 21	Non-Linear displacement(mm) Node 21	The difference%
0	0	0	0.000
10	0.641	0,641	0.000
20	1.282	1.283	0.078
30	1.922	1.925	0.156
40	2.563	2.567	0.156
50	3.204	3.210	0.187
60	3.845	3.854	0.234
70	4.486	4.498	0.267
80	5.126	5.142	0.312
90	5.767	5.788	0.364
100	6.408	6.434	0.406
110	7.049	7.080	0.439

Table (5-1b): Vertical reaction linear and non-linear for ascending roof

Load (kN)	Linear reaction fx Node25(mm)	Non-Linear reaction fx Node25(mm)	The Difference %	Linear reaction fy Node25(mm)	Non-Linear reaction fy Node25(mm)	The Difference %
0	0	0	0	0	0	0
10	13.1026	13.1090	0.048	26.5513	26.5513	0.002
20	26.2051	26.2308	0.981	53.1029	53.1053	0.005
30	39.3077	39.3954	0.146	79.6538	79.6600	0.007
40	52.4102	52.5128	0.195	106.2051	106.2160	0.01
50	65.5128	65.6728	0.244	132.7564	132.7733	0.012
60	78.6154	78.8454	0.292	159.3077	159.3317	0.015
70	91.7179	92.0304	0.340	185.8590	185.8913	0.017
80	104.8205	105.2273	0.388	212.4102	212.4517	0.019
90	117.9231	118.4355	0.434	238.9615	239.0127	0.021
100	131.0256	131.6534	0.479	265.5128	265.5733	0.022
110	144.1282	144.8802	0.521	292.0641	292.1336	0.023

Table (5-1c): Vertical linear and non-linear force for ascending roof

Load (kN)	Linear force Fx Bar 13 node15 (kN)	Non-Linear force Fx Bar 13 node15 (kN)	The difference %	Linear force Fy Bar 21 node20 (kN)	Non-Linear force Fy Bar 21 node20 (kN)
0	0	0	0	0	0
10	15.1726	15.1787	0.040	0.0092	0.0028
20	30.3453	30.3697	0.080	0.0184	0.0049
30	45.5179	45.5730	0.121	0.0277	0.0059
40	60.6906	60.7886	0.161	0.0369	0.0177
50	75.8632	76.0168	0.202	0.0461	0.0396
60	91.0358	91.2576	0.243	0.553	0.0688
70	106.2085	106.5113	0.285	0.0645	0.1058
80	121.3811	121.7783	0.327	0.0738	0.1511
90	136.5537	137.0595	0.370	0.0830	0.2066
100	151.7264	152.3575	0.415	0.0922	0.2769
110	166.8990	167.7104	0.4862	0.1014	0.4170

The results of linear and nonlinear analysis for Fy is very small so we are neglected

5.3 Curved roof:

The Curved roof was represented by a finite model with 61 nodes and 200 elements with pin - joint supports. The geometry, materials properties and loading are shown in fig (5-2). Autodesk Robot structure 2015 was used to carry out the linear and non-linear analysis. The results obtained for maximum vertical displacement, reaction andelement force due to vertical load are shown and compared in tables (5-2a), (5-2b) and (5-2c) respectively.

The load was applied in 11 increments, each of 10kn for linear and nonlinear analysis. 10iteralions were required for convergence with in each increment for nonlinear analysis.

Table(5-2a): Vertical linear and non-linear displacement for Curved roof

Load(kN)	Linear displacement(mm) Node 49	Non-Lineardisplacement(mm) Node 49	The Difference%
0	0	0	0.000
10	0.273	0.273	0.000
20	0.545	0.545	0.000
30	0.818	0.818	0.000
40	1.091	1.091	0.000
50	1.363	1.364	0.073
60	1.636	1.637	0.061
70	1.909	1.9	0.052
80	2.181	2.182	0.045
90	2.454	2.455	0.04
100	2.727	2.728	0.04
110	2.999	3.001	0.07

Table (5-2b): Vertical reaction linear and non-linear for Curved roof

Load (kN)	Linear reaction Fx Node47 (kN)	Non-Linear reaction Fx Node47 (kN)	The Difference %	Linear reaction Fy Node47 (kN)	Non-Linear reaction Fy Node47 (kN)	The Difference %
0	0	0	0	0	0	0
10	10.887	10.8863	0.001	7.6512	7.6511	0.001
20	21.7713	21.7738	0.011	15.3023	15.3021	0.001
30	32.6570	32.6625	0.016	22.9535	22.9530	0.002
40	43.5427	43.5524	0.022	30.6047	30.637	0.003
50	54.4284	54.4436	0.027	38.2558	38.2544	0.003
60	65.3140	65.3360	0.033	45.9070	45.9549	0.004
70	76.1997	76.2296	0.039	53.5582	53.5553	0.005
80	87.054	87.1244	0.080	61.2094	61.2055	0.006
90	97.9711	98.0204	0.05	68.8605	68.8556	0.007
100	108.8567	108.9176	0.055	76.5117	76.5056	0.008
110	119.7424	119.8161	0.061	84.1629	84.1554	0.009

Table (5-2c): Vertical force linear and non-linear for Curved roof

Load (kN)	Linear force Fx Bar 70node48 (kN)	Non-Linear force Fx Bar 70 node48 (kN)	The Difference %	Linear force Fy Bar 41 node10 (kN)	Non-Linear force Fy Bar 41 node10 (kN)
0	0	0	0	0	0
10	9.6997	9.7003	0.006	0.0115	0.0113
20	19.3993	19.4017	0.0124	0.0229	0.0221
30	29.099	29.1044	0.018	0.0344	0.0326
40	38.7986	38.8082	0.024	0.0459	0.0426
50	48.4983	48.5133	0.030	0.0574	0.0522
60	58.1979	58.2171	0.037	0.0688	0.0614
70	67.8976	67.9271	0.043	0.0803	0.0702
80	77.5972	77.6358	0.049	0.0918	0.0785
90	87.2969	87.3457	0.055	0.1032	0.0865
100	97.9965	97.0569	0.062	0.1147	0.094
110	106.6962	106.7693	0.068	0.1262	0.1012

The results of linear and nonlinear analysis for Fy is very small so we are neglected.

5.4 Star dome roof:

The Star dome roof was represented by finite model (a)with13nodes and 24 elements with pin joint supports , (b)with19 nodes and 36 elements with pin joint supports, (c)with27 nodes and 43 elements with pinjoint supports. The geometry, materials properties and loading are shown in fig (5-3a),(5-3b)and(5-3c). Autodesk Robot structure 2015 was used to carry out the linear and non-linear analysis. The results obtained for maximum vertical displacement, reaction and stress due to vertical load are shown and compared in tables (5-3a),(5-3b), (5-3c), (5-3d) and(5-3e) respectively .

The load was applied in 11 increments, each of 20kN for linear and nonlinear analysis. 10iteralions were required for convergence with in each increment for nonlinear analysis.

Table (5-3a): Vertical linear (a), linear (b) and linear (c) displacement for star roof

Load(kN)	Linear (a) displacement(mm) Node 4	Linear (b) displacement(mm) Node 4	Linear (c) displacement(mm) Node 4
220	23.502	23.02	22.319

Table (5-3b): Vertical linear and non-linear displacement for star roof

Load (kN)	Linear Displacement (mm) Node 4	Non-Linear Displacement (mm) Node 4	The Difference %
0	0	0	0
20	2.137	2.158	0.982
40	4.273	4.363	2.106
60	6.410	6.616	3.213
80	8.546	8.921	4.388
100	10.683	11.284	5.625
120	12.819	13.715	6.989
140	14.956	16.214	8.411
160	17.092	18.792	9.952
180	19.229	21.465	13.328
200	21.365	24.251	13.508
220	23.502	27.222	15.825

Table (5-3c): Vertical linear (c) and non-linear (c) displacement for star roof

Load (KN)	Linear (C)Displacement (mm) Node 4	Non-Linear (c)Displacement (mm) Node 4	The Difference %
0	0	0	0
20	2.029	2.052	1.133
40	4.058	4.152	2.316
60	6.087	6.305	3.581
80	8.116	8.514	4.903
100	10.145	10.785	6.308
120	12.174	13.131	7.861
140	14.203	15.552	9.497
160	16.232	18.063	11.28
180	18.261	20.678	13.235
200	20.290	23.417	15.411
220	22.319	26.310	17.881
240	24.348	29.409	20.786
260	26.377	32.796	24.335

Table (5-3d): Vertical linear and non-linear reaction for star roof

Load (k N)	Linear reaction Fx Node11(kN)	Non-Linear reaction Fx Node11(kN)	The Difference %	Linear reaction Fy Node1(kN)	Non-Linear reaction Fy Node1(kN)	The Differenc e %
0	0	0	0	0	0	0
20	2.9728	2.9554	0.588	8.0393	8.0688	0.366
40	5.9456	5.8746	1.208	16.0787	16.1992	0.749
60	8.9184	8.7550	1.866	24..1180	24.3954	1.150
80	11.8912	11.5936	2.566	32.1574	32.6626	1.157
100	14.8640	14.3867	3.317	40.1967	41.0070	2.115
120	17.8368	17.1254	4.154	48.2361	49.4421	2.500
140	20.8096	19.8094	5.049	56.2754	57.9691	3.009
160	23.7824	22.4268	6.044	64.3148	66.6049	3.56
180	26.7552	24.9615	7.185	72.3541	75.3691	4.167
200	29.7280	27.3737	8.600	80.3935	84.2968	4.855
220	32.7008	29.2206	11.910	88.4328	93.6046	5.848

Table (5-3e): linear and non-linear stress for star roof

Load (kN)	Linear stress max Bar 1 Node 2 (Mpa)	Non- Linear stress max Bar 1 Node 2 (Mpa)	The Difference %	Linear stress min Bar 21 Node 2 (Mpa)	Non- Linear stress min Bar 21 Node 2 (Mpa)	The Difference %
0	0	0	0	0	0	0
20	3.8888	3.8485	1.047	3.7817	3.8511	1.835
40	7.7775	7.6090	2.214	7.5634	7.8494	3.781
60	11.6663	11.2686	3.529	11.3451	12.008	5.779
80	15.5551	14.8115	5.02	15.1268	16.3499	8.085
100	19.4439	18.2182	6.727	18.9086	20.8914	10.486
120	23.3326	21.4638	8.706	22.6903	25.6696	13.13
140	27.2214	24.5161	11.034	26.4720	30.7074	15.999
160	31.1102	27.3302	13.830	30.2537	36.0560	19.178
180	34.9989	29.8348	17.309	34.0354	41.7809	22.757
200	38.8877	31.8623	22.049	37.8171	47.9945	26.912
220	42.7765	34.4955	24.006	41.5988	55.4348	33.26

5.5 Circular dome roof:

TheCircular dome roof was presented by finite model with97 nodes and 264 elements with pin - joint supports. The geometry, materials properties and loading are shown in fig (5-4). Autodesk Robot structure 2015 was used to carry out the linear and non-linear analysis. The results obtained for maximum vertical displacement, reaction, force and stress due to vertical load are shown and compared in tables (5-4a) , (5-4b) ,(5-4c)and (5-4d) respectively.

The load was applied in 7 increments, each of 5KN for linear and nonlinear analysis. 10iteralions were required for convergence with in each increment for nonlinear analysis.

Table (5-4a): Vertical linear and non-linear displacement for Circular dome roof

Load (kN)	Linear Displacement Node 97 (mm)	Non-Linear Displacement node97 (mm)	The Difference %
0	0	0	0
5	6.581	6.772	2.902
10	13.161	13.976	6.192
15	19.742	21.708	9.958
20	26.322	30.107	14.379
25	32.903	39.383	19.694
30	39.484	49.888	26.349
35	46.064	62.305	35.25

Table (5-4b): Vertical reaction linear and non-linear for Circular dome roof

Load (kN)	Linear reaction Fx Node13(kN)	Non-Linear reaction Fx Node13(kN)	The Difference %	Linear reaction Fy Node10(kN)	Non-Linear reaction Fy Node10(kN)	The Difference %
0	0	0	0	0	0	0
5	0.2002	0.2003	0.05	0.2509	0.2508	0.039
10	0.4004	0.4008	0.099	0.5019	0.5014	0.099
15	0.6006	0.6016	0.166	0.7528	0.7518	0.133
20	0.8008	0.8027	0.237	1.0037	1.0018	0.189
25	1.009	1.0123	0.327	1.2546	1.2515	0.247
30	1.2011	1.2064	0.441	1.5056	1.5007	0.326
35	1.4013	1.4092	0.563	1.7565	1.7492	0.417

Table (5-4c): Vertical linear and non-linear force for Circular dome roof.

Load (kN)	Linear force Fx Bar 84 node83 (kN)	Non-Linear force Fx Bar 84 node83 (kN)	The Difference %	Linear force Fy Bar 105 node74 (kN)	Non-Linear force Fy Bar 105 node74 (kN)
0	0	0	0	0	0
5	14.1864	14.729	3.640	0.0169	0.0008
10	28.3728	30.5753	7.627	0.0338	0.0120
15	42.5591	47.8766	12.494	0.0506	0.0131
20	56.7455	66.9843	18.043	0.0675	0.0283
25	70.9319	88.4591	24.724	0.0844	0.0796
30	85.1183	113.2909	33.098	0.1013	0.1620
35	99.3047	143.3099	44.313	0.1181	0.2925

The results of linear and nonlinear analysis for Fy is very small so we are neglected.

Table (5-4c) : linear and non-linear stress for Circular dome roof

Load (kN)	Linear stress max Bar 144 Node 97 (Mpa)	Non- Linear stress max Bar 144Node 97 (Mpa)	The Difference %	Linear stress min Bar 85 Node 85 (Mpa)	Non- Linear stress min Bar 85 Node 85 (Mpa)	The Difference %
0	0	0	0	0	0	0
5	4.8623	4.8325	0.616	4.9504	5.1348	3.725
10	9.7246	9.6023	1.273	9.9007	10.6852	7.923
15	14.5870	14.3046	1.974	14.8511	16.7386	12.709
20	17.4039	18.9372	2.464	16.8014	23.4205	18.277
25	24.3116	24.1167	0.808	24.7518	30.9168	24.907
30	29.1739	29.9415	0.202	29.7022	39.5329	33.097
35	34.0363	32.5222	4.655	34.6525	49.8401	43.828

5.7 Comments on Results:

For examples one and two, the non-linear solution diverged, this may be due to slenderness of members, which indicates buckling and hence failure in design.

In examples three and four there is a clear effect of the non- linear analysis. This is especially true for the displacements and forces.

The reactions show no clear difference between the linear and non-linear results.

To check the finite element model, two models of structure were analyzed under linearly maximum load. The two models were obtained by increasing the number of members. Then the results of the three models are compared to check monotonic convergence.

CHAPTER SIX

ANALYSIS AND DISCUSSION OF RESULTS

6.1 Ascending roof towards the field:

The Ascending roof towards the field was analyzed for linear and non- linear geometry using Autodesk Robot structure 2015 program as stated in chapter four. The non-linear solution converges for loads up to 110 kN.for load more than 110kN the solution diverges .this may be an indication that the flat roof geometry is not suitable for geometrically non-linear situations.

-The difference between displacements for linear and nonlinear results is not more than 0.5% in this case we cannot find the effect of nonlinear analysis.

-The difference between reactions for linear and nonlinear results is not more than 0.6% in this case we cannot find the effect of nonlinear analysis.

-The difference between forces for linear and nonlinear results is not more than 0.6% in this case find the effect of nonlinear analysis.

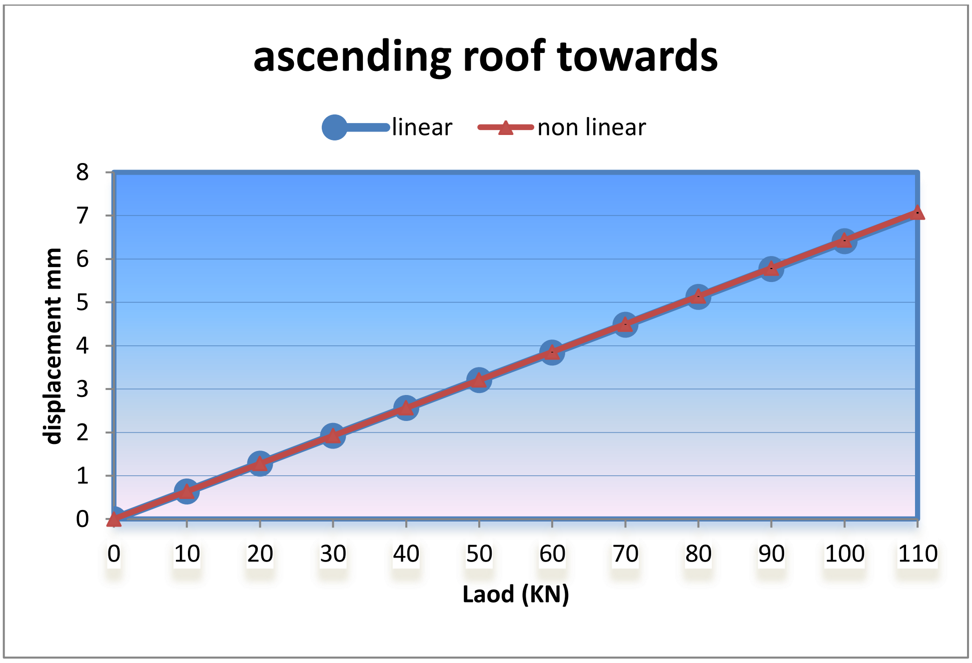


Fig (6-1a) Linear and Nonlinear displacement due to vertical load for Ascending roof

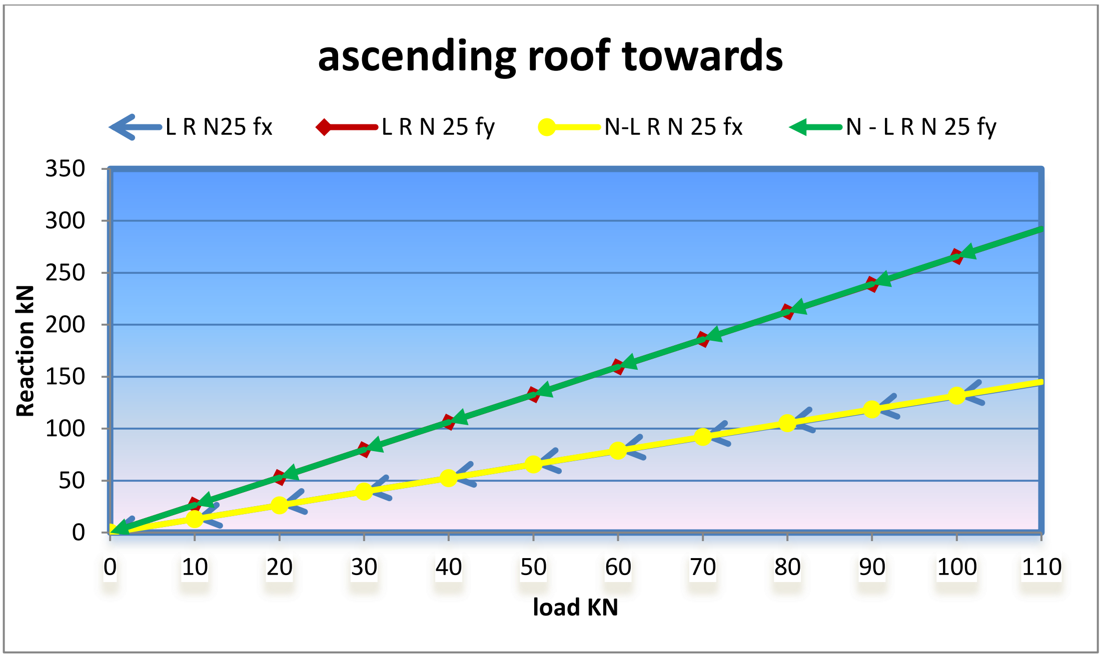


Fig (6-1b) Linear and Nonlinear reaction due to vertical load for Ascending roof

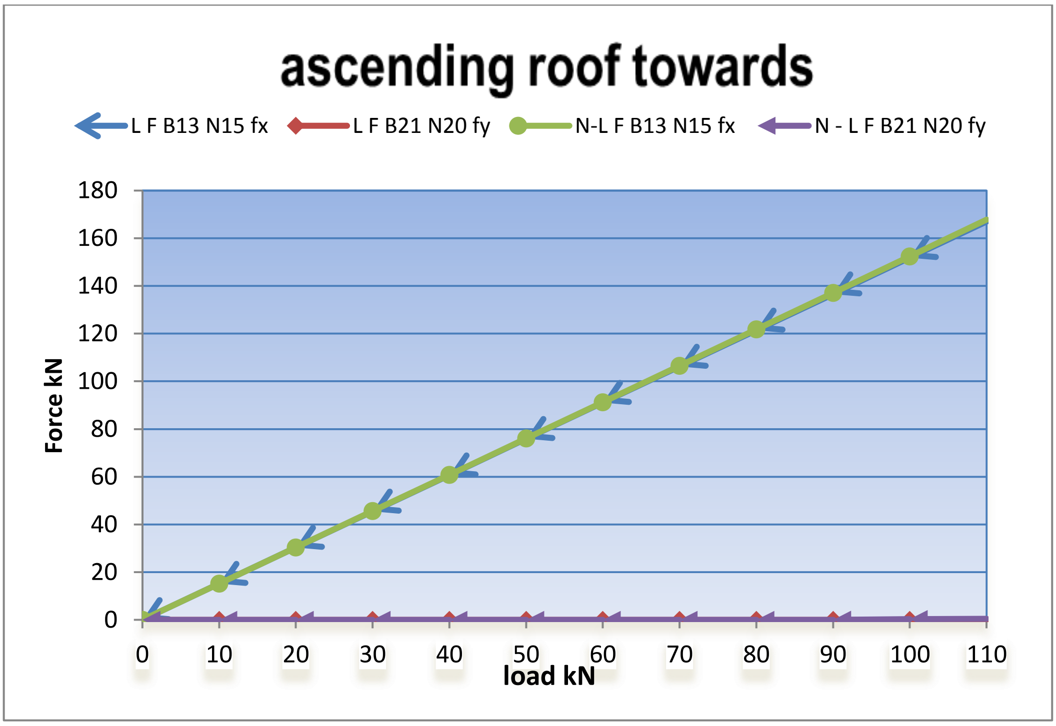


Fig (6-1c) Linear and Nonlinear force due to vertical load for Ascending Roof.

6.2 Curved roof:

The Curved roof was analyzed for linear and non- linear geometry using Autodesk Robot structure 2015 as stated in chapter four. Similarly to the case 1 the non-linear solution converges for load up to 110 kN.for load more than110kN the solution diverges ,this may be an indication that the flat roof geometry is not suitable for geometry non-linear situations.

- The difference between reactions for linear and nonlinear results is not more than 0.3% in this case we cannot find the effect of nonlinear analysis.

-The difference between reactions and forces for linear and nonlinear results is not more than 0.1% in this case we cannot find the effect of nonlinear analysis.

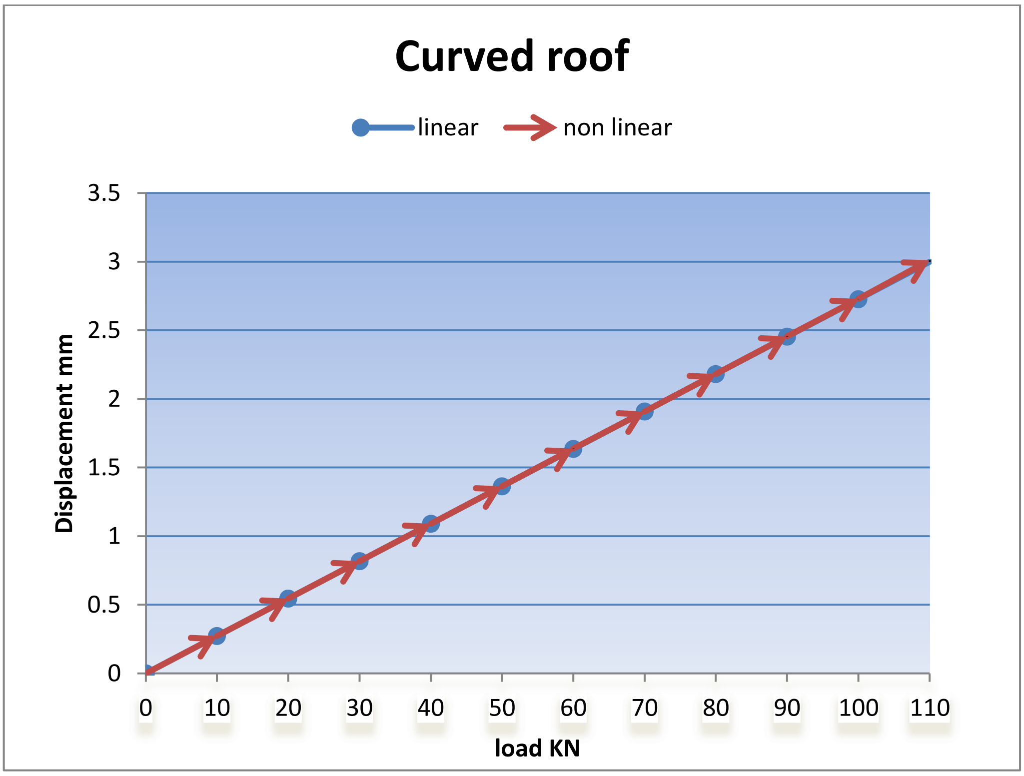


Fig (6-2 a) Linear and Nonlinear displacement due to vertical load for Curved roof.

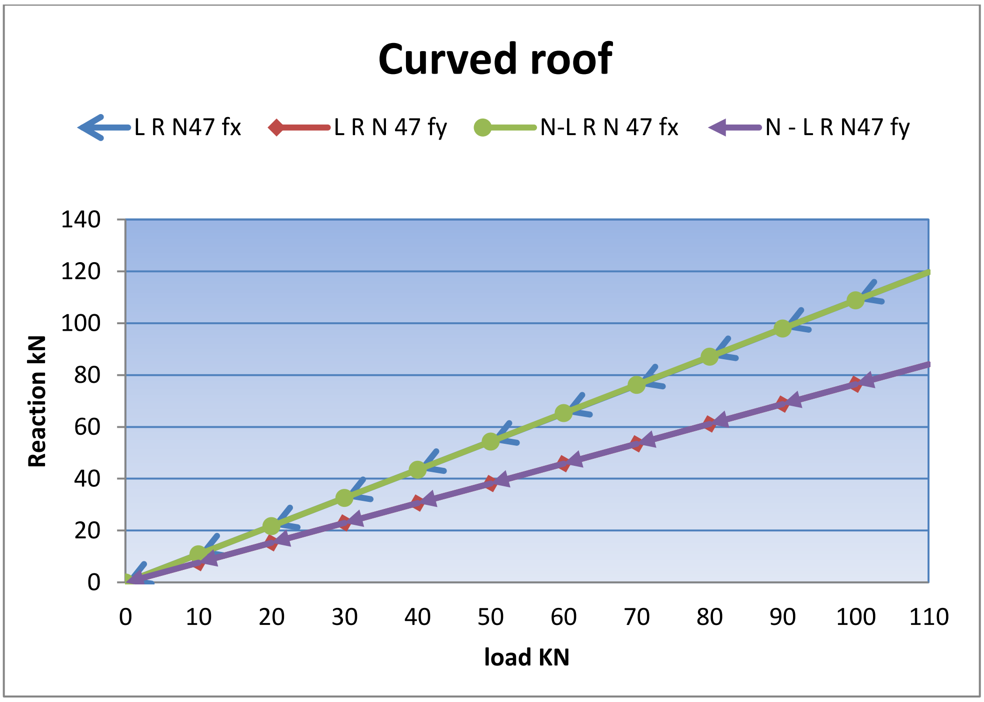


Fig (6-2 b) Linear and Nonlinear reaction due to vertical load for Curved roof.

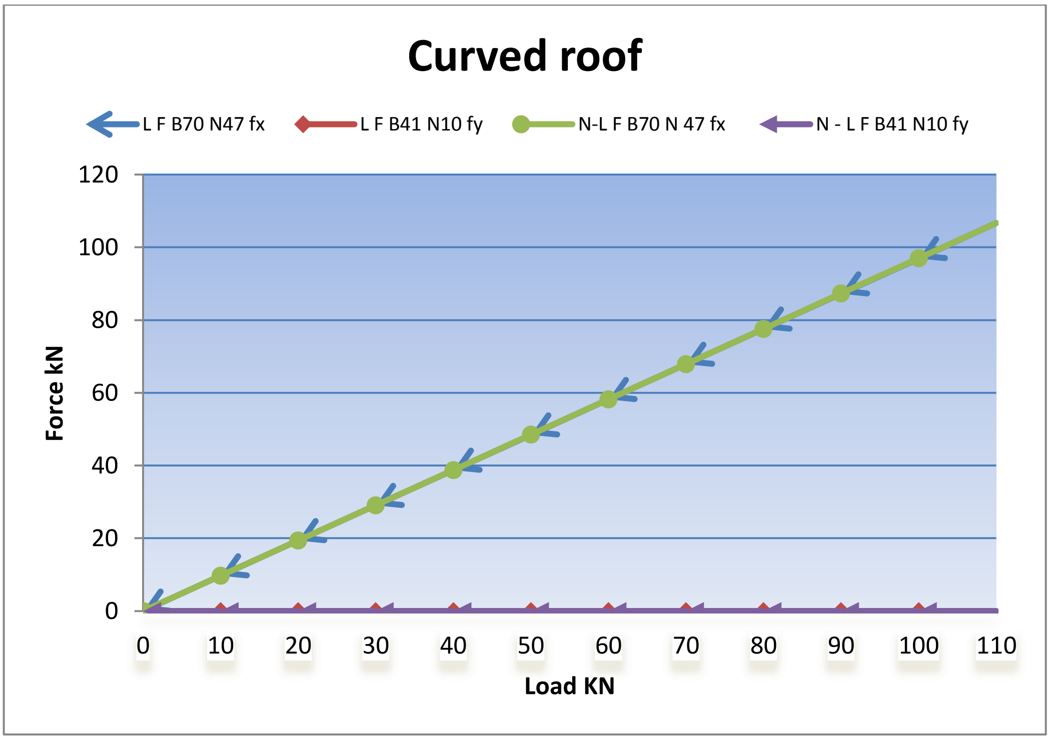


Fig (6-2 c) Linear and Nonlinear force due to vertical load for Curved roof.

6.3 Star Dome Roof:

As can be seen from the linear and non-linear analysis results:

In the table (5-3a, 5-3b, 5-3c,5-3d,5-3e) , The star dome roof figures (6-3a ,6-3b, 6-3c,6-3d ,6-3e) is suitable for non-linear analysis :

- The difference between displacements for linear and nonlinear results is 15% in this case we can find the effect of nonlinear analysis clearly. The displacements in nonlinear more than linear.

-The difference between reactions for linear and nonlinear results is 11%**.**

-The difference between max stresses for linear and nonlinear results is 24% .and the stresses in non- linear less than linear.

When increasing the number of members thedisplacements are decrease.

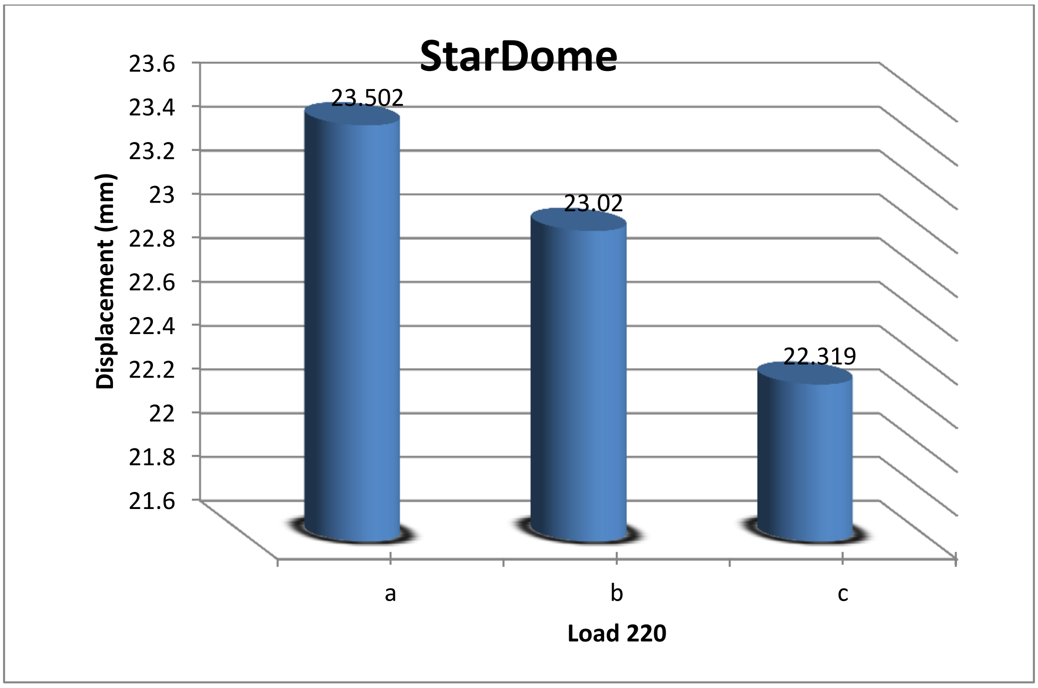


Fig (6-3 a) Linear displacement (a,b,c) due to vertical load 220kN .

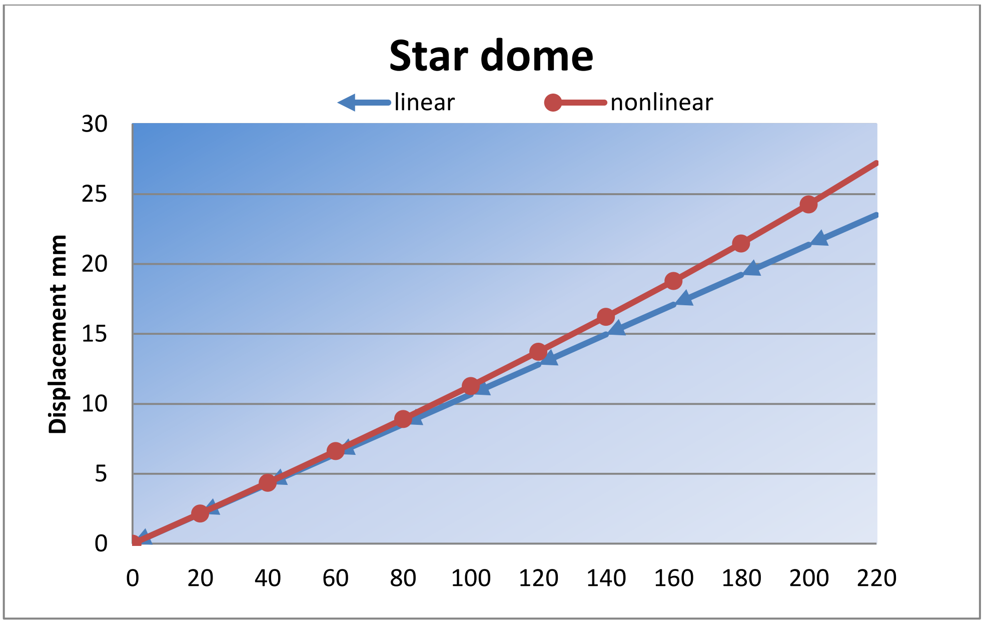


Fig (6-3 b) Linear and Nonlinear displacement due to vertical load for Star dome roof for (a).

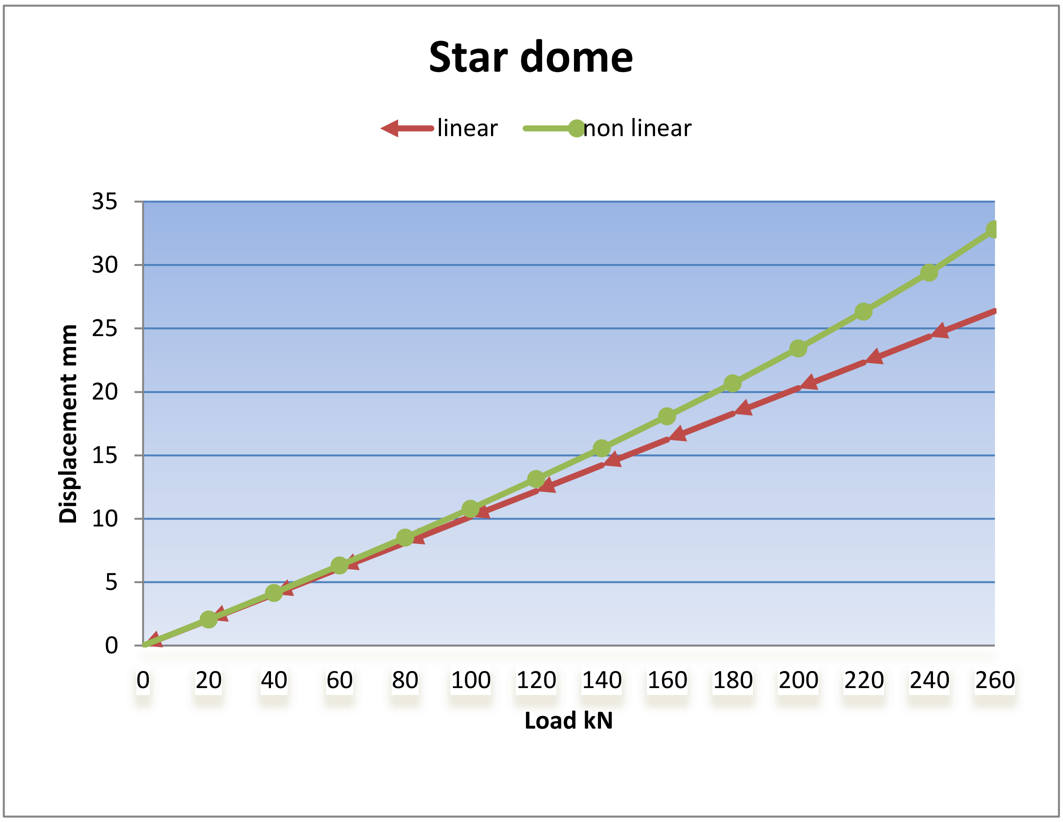


Fig (6-3 c) Linear and Nonlinear displacement due to vertical load for Star dome roof(c).

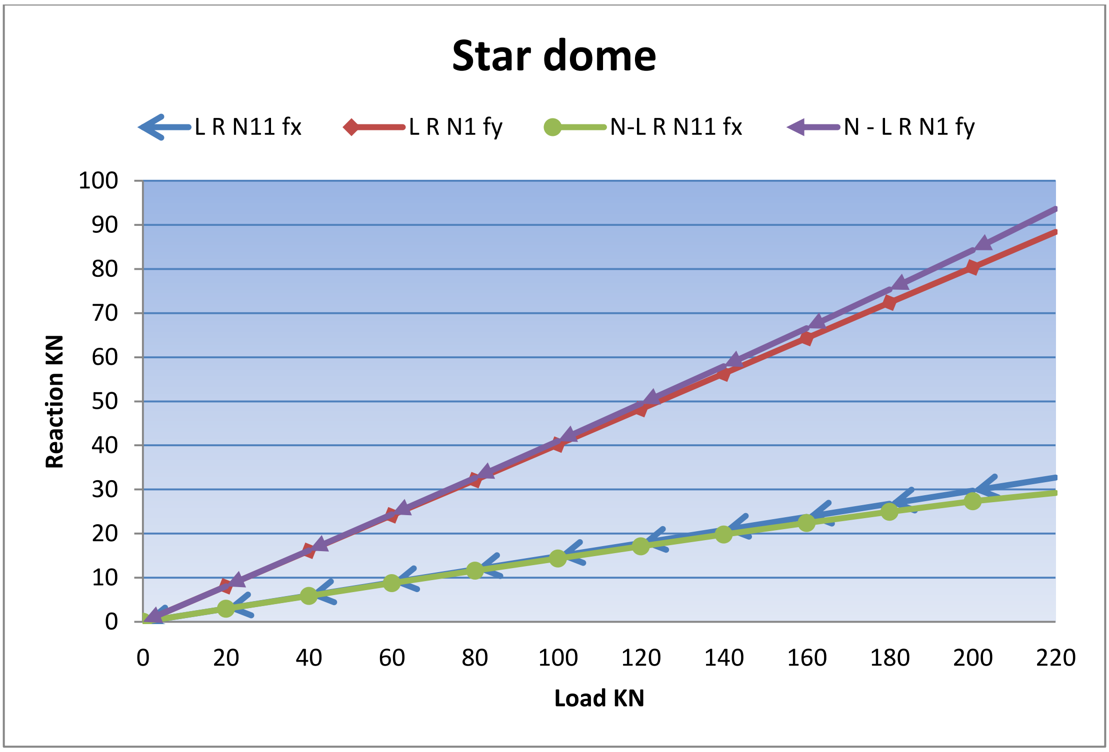


Fig (6-3 d) Linear and Nonlinear reaction due to vertical load for Star dome roof.

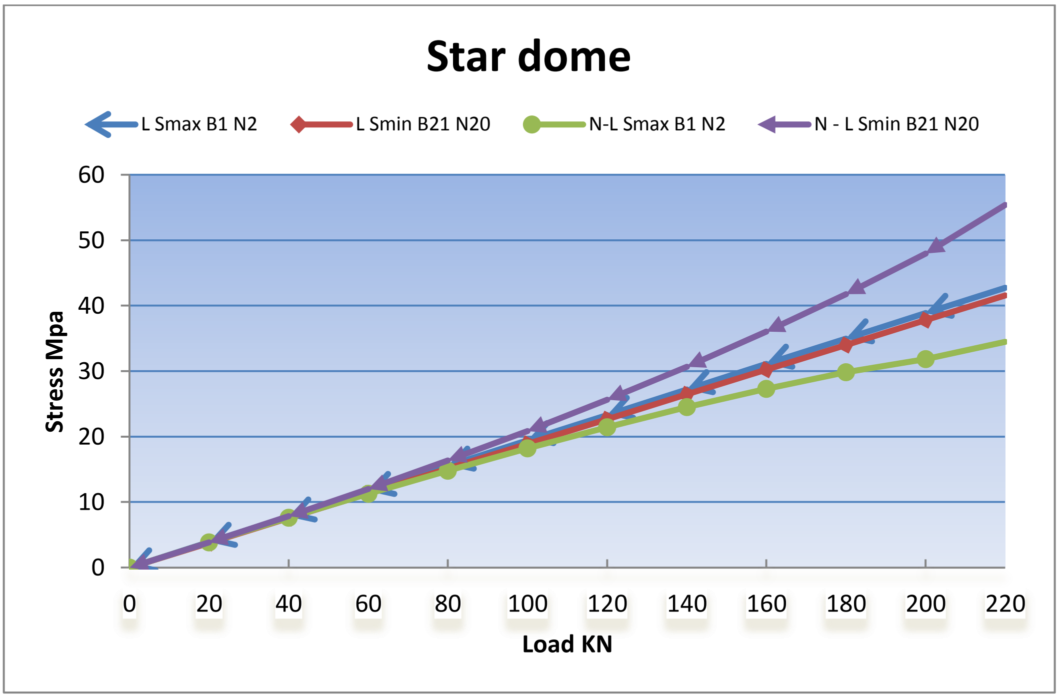


Fig (6-3 e) Linear and Nonlinear stress due to vertical load for Star dome roof.

5.4: Circular dome roof:

As can be seen from the linear and non-linear analysis results:

In the table (5-4a, 5-4b, 5-4c, 5-4d), The Circular dome roof figures (6-4a,6-4b, 6-4c,6-4d) is suitable for non-linear analysis it can be seen that :

-The difference between displacements for linear and nonlinear results is more than 35% in this case we can find the effect of nonlinear analysis. The results of displacements in nonlinear more than linear**.**

-The difference between reactions for linear and nonlinear results is 0.6%**.**

-The difference between max stresses for linear and nonlinear results 5% .and the stresses in non- linear less than linear.

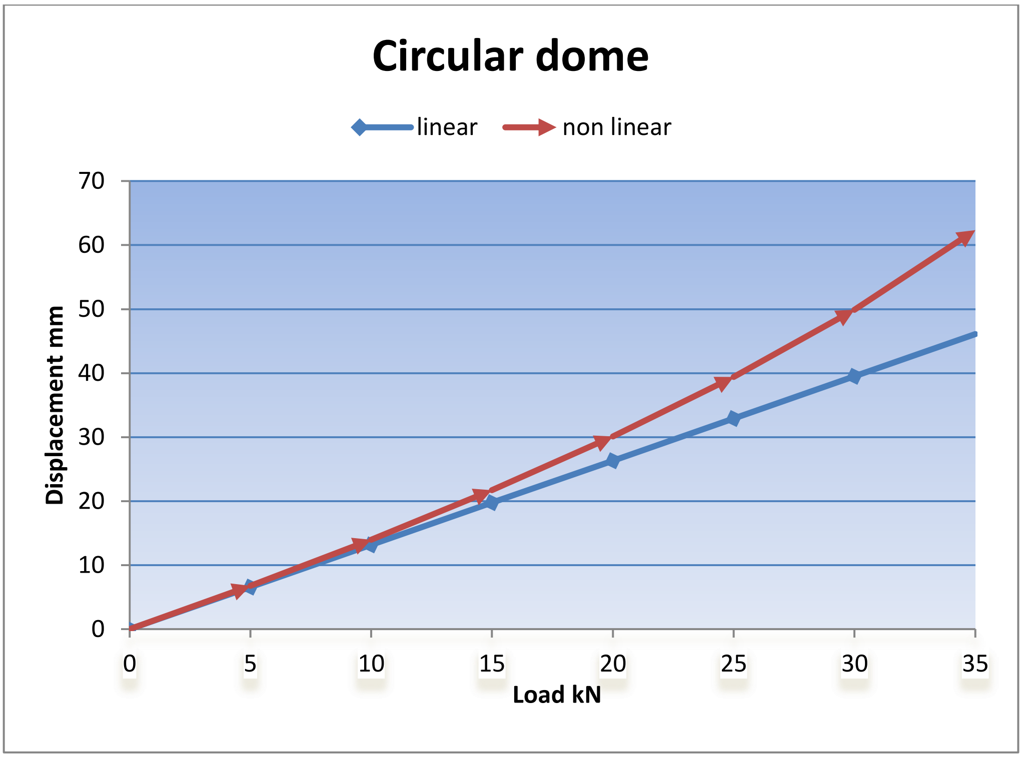


Fig (6-4 a) Linear and Nonlinear displacement due to vertical load for Circular dome roof.

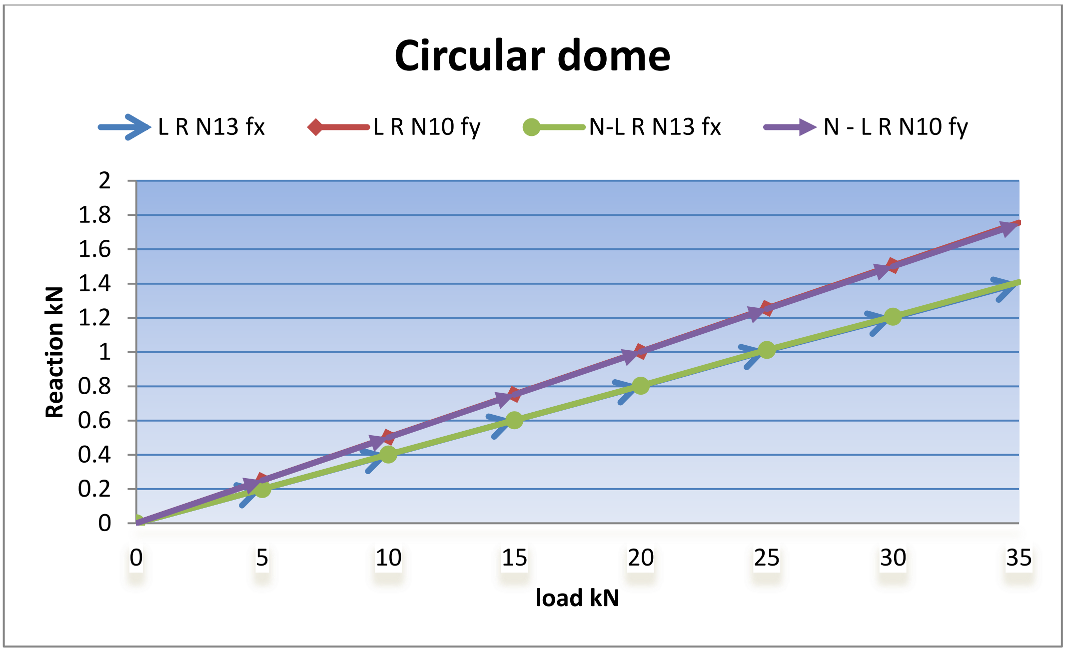


Fig (6-4 b) Linear and Nonlinear reaction due to vertical load for Circular dome roof.

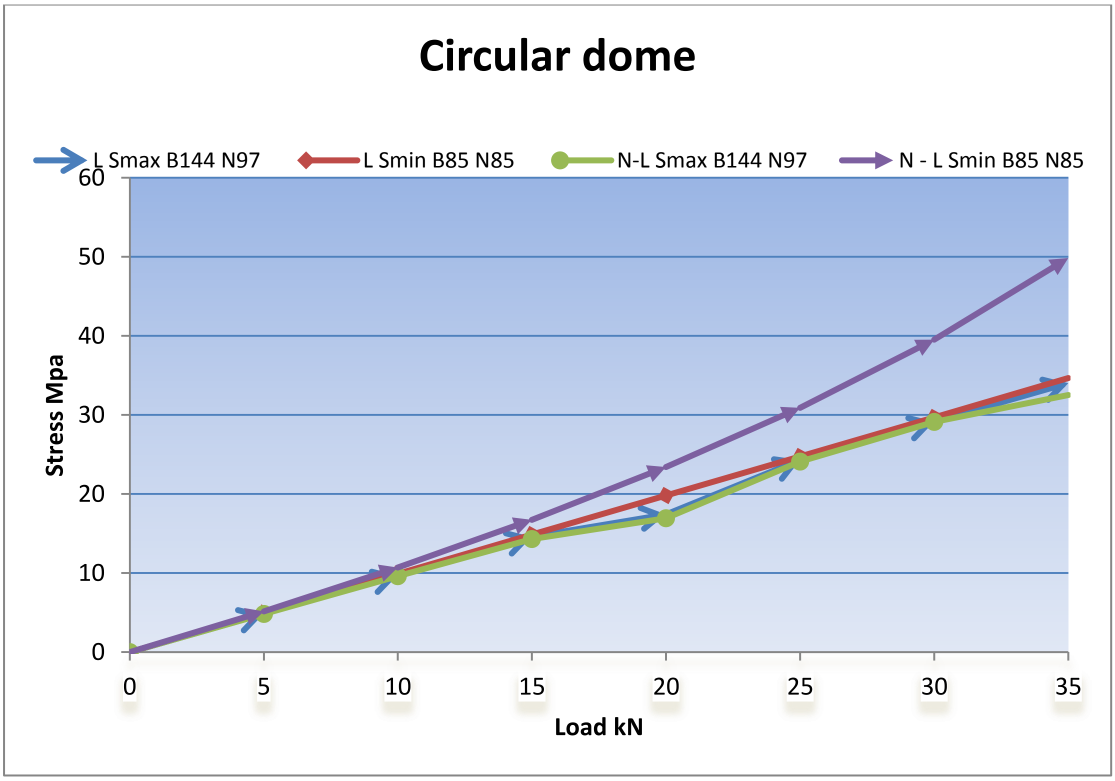


Fig (6-4 c) Linear and Nonlinear stress due to vertical load for Circular dome roof.

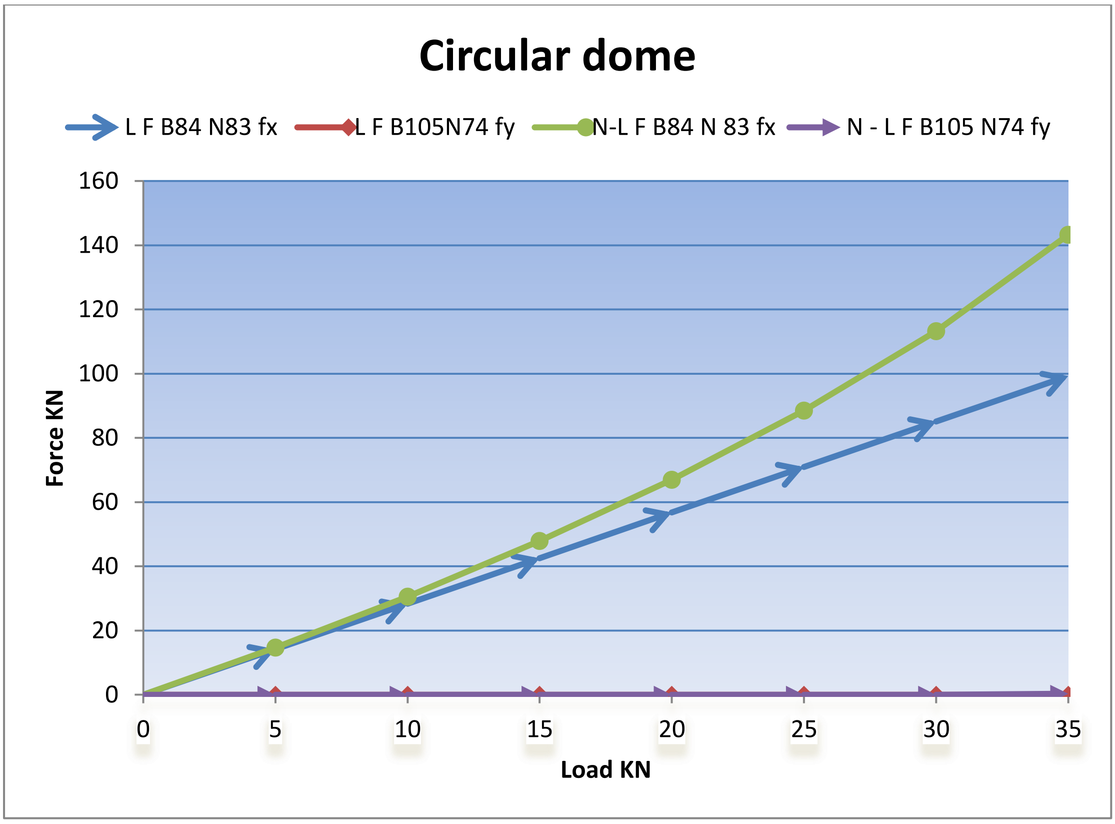


Fig (6-4 d) Linear and Nonlinear force due to vertical load for Circular dome roof.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATIONS

7.1 Conclusion:

In this study, four cases of stadia dome roofs were selected namely Ascending roof towards the field, Curved roof, Star dome roof and Circular dome roof. The cases were analyzed for linear and nonlinear geometry using Robot structure 2015 program. The results obtained were analyzed and discussed.

* The comparison of results of the linear displacements due to incremental load with results of the nonlinear displacements, forAscending roof towards the field showed small difference (0.4%).

* The comparison of results of the linear forces due to incremental load with results of the nonlinear forces, forAscending roof towards the field showed small difference (0.5%).

* The comparison of results of the linear displacements due to incremental load with results of the nonlinear displacements, forCurved roof showed small difference (0.3%).

* The comparison of results of the linear forces due to incremental load with results of the nonlinear forces, forCurved roof showed small difference (0.7%).

* The results of linear reaction due to incremental load for all cases dome (Ascending roof towards the field, Curved roof, Star dome roof and Circular dome roof) and the results of nonlinear reaction it showed good agreement.

* The nonlinear displacements for Star dome roof are greater about 15% for Star dome roof compared with linear displacement. The more members increase the more loads the model carries, the greater the difference between the linear and nonlinear analysis.

* The comparison of results between the linear Max stresses and the nonlinear max stresses for Star dome roof the linear is greater than nonlinear (24%).

*The nonlinear displacements for Circular dome roof are greater about 35% for Star dome roof compared with linear displacement.

* The comparison of results of the linear forces due to incremental load with results of the nonlinear forces, forCircular dome roof showed big difference (44%).

* The comparison of results between the linear Max stresses and the nonlinear max stresses for Circular dome roof the linear is greater than nonlinear (5%).

7.2 Recommendations:

From result of study: i recommended to:

1. Use the Star dome roof and/ or Circular dome roof for nonlinear analysis.

2. Use nonlinear analysis of stadia dome roofs in order to obtain economical solutions.

For future studies it is recommended to:

1. Investigate the causes of failure of Ascending roof towards the field and Curved roof in nonlinear large displacement analysis.

2. Carry out more studies on the optimization of stadia dome roof because it affects stability of analysis.

3. More research to know the most appropriate for the Sudan from the stadiums in particular and Sudan is volatile climate.

4. Study of the effect of assuming that the joints are rigid and semi-rigid by adopting a nonlinear finite formulation of space frame element.

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Appendix

1.1CaseOne: Ascending roof towards the field

Node 39, Elements 120

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
1	1	2	exaple roof towards	S460	0.0	Simple bar	Bar
2	2	3	exaple roof towards	S460	0.0	Simple bar	Bar
3	3	4	exaple roof towards	S460	0.0	Simple bar	Bar
4	4	5	exaple roof towards	S460	0.0	Simple bar	Bar
5	5	6	exaple roof towards	S460	0.0	Simple bar	Bar
6	7	8	exaple roof towards	S460	0.0	Simple bar	Bar
7	8	9	exaple roof towards	S460	0.0	Simple bar	Bar
8	9	10	exaple roof towards	S460	0.0	Simple bar	Bar
9	10	11	exaple roof towards	S460	0.0	Simple bar	Bar
10	11	12	exaple roof towards	S460	0.0	Simple bar	Bar
11	13	14	exaple roof towards	S460	0.0	Simple bar	Bar
12	14	15	exaple roof towards	S460	0.0	Simple bar	Bar
13	15	16	exaple roof towards	S460	0.0	Simple bar	Bar
14	16	17	exaple roof towards	S460	0.0	Simple bar	Bar
15	17	18	exaple roof towards	S460	0.0	Simple bar	Bar
16	35	36	exaple roof towards	S460	0.0	Simple bar	Bar
17	36	37	exaple roof towards	S460	0.0	Simple bar	Bar
18	37	38	exaple roof towards	S460	0.0	Simple bar	Bar
19	38	39	exaple roof towards	S460	0.0	Simple bar	Bar
20	19	20	exaple roof towards	S460	0.0	Simple bar	Bar
21	20	21	exaple roof towards	S460	0.0	Simple bar	Bar
22	21	22	exaple roof towards	S460	0.0	Simple bar	Bar
23	22	23	exaple roof towards	S460	0.0	Simple bar	Bar
24	23	24	exaple roof towards	S460	0.0	Simple bar	Bar
25	25	26	exaple roof towards	S460	0.0	Simple bar	Bar
26	26	27	exaple roof towards	S460	0.0	Simple bar	Bar
27	27	28	exaple roof towards	S460	0.0	Simple bar	Bar
28	28	29	exaple roof towards	S460	0.0	Simple bar	Bar
29	30	31	exaple roof towards	S460	0.0	Simple bar	Bar
30	31	32	exaple roof towards	S460	0.0	Simple bar	Bar
31	32	33	exaple roof towards	S460	0.0	Simple bar	Bar
32	33	34	exaple roof towards	S460	0.0	Simple bar	Bar
33	1	7	exaple roof towards	S460	0.0	Simple bar	Bar
34	2	8	exaple roof towards	S460	0.0	Simple bar	Bar
35	3	9	exaple roof towards	S460	0.0	Simple bar	Bar
36	4	10	exaple roof towards	S460	0.0	Simple bar	Bar
37	5	11	exaple roof towards	S460	0.0	Simple bar	Bar
38	6	12	exaple roof towards	S460	0.0	Simple bar	Bar
39	7	13	exaple roof towards	S460	0.0	Simple bar	Bar
40	8	14	exaple roof towards	S460	0.0	Simple bar	Bar
41	9	15	exaple roof towards	S460	0.0	Simple bar	Bar
42	10	16	exaple roof towards	S460	0.0	Simple bar	Bar
43	11	17	exaple roof towards	S460	0.0	Simple bar	Bar
44	12	18	exaple roof towards	S460	0.0	Simple bar	Bar
45	13	19	exaple roof towards	S460	0.0	Simple bar	Bar
46	14	20	exaple roof towards	S460	0.0	Simple bar	Bar
47	15	21	exaple roof towards	S460	0.0	Simple bar	Bar
48	16	22	exaple roof towards	S460	0.0	Simple bar	Bar
49	17	23	exaple roof towards	S460	0.0	Simple bar	Bar
50	18	24	exaple roof towards	S460	0.0	Simple bar	Bar
51	25	30	exaple roof towards	S460	0.0	Simple bar	Bar
52	26	31	exaple roof towards	S460	0.0	Simple bar	Bar
53	27	32	exaple roof towards	S460	0.0	Simple bar	Bar
54	28	33	exaple roof towards	S460	0.0	Simple bar	Bar
55	29	34	exaple roof towards	S460	0.0	Simple bar	Bar
56	30	35	exaple roof towards	S460	0.0	Simple bar	Bar
57	31	36	exaple roof towards	S460	0.0	Simple bar	Bar
58	32	37	exaple roof towards	S460	0.0	Simple bar	Bar
59	33	38	exaple roof towards	S460	0.0	Simple bar	Bar
60	34	39	exaple roof towards	S460	0.0	Simple bar	Bar

61	25	1	exaple roof towards	S460	0.0	Simple bar	Bar
62	25	2	exaple roof towards	S460	0.0	Simple bar	Bar
63	25	7	exaple roof towards	S460	0.0	Simple bar	Bar
64	25	8	exaple roof towards	S460	0.0	Simple bar	Bar
65	26	2	exaple roof towards	S460	0.0	Simple bar	Bar
66	26	3	exaple roof towards	S460	0.0	Simple bar	Bar
67	26	8	exaple roof towards	S460	0.0	Simple bar	Bar
68	26	9	exaple roof towards	S460	0.0	Simple bar	Bar
69	27	3	exaple roof towards	S460	0.0	Simple bar	Bar
70	27	9	exaple roof towards	S460	0.0	Simple bar	Bar
71	27	4	exaple roof towards	S460	0.0	Simple bar	Bar
72	27	10	exaple roof towards	S460	0.0	Simple bar	Bar
73	28	4	exaple roof towards	S460	0.0	Simple bar	Bar
74	28	5	exaple roof towards	S460	0.0	Simple bar	Bar
75	28	10	exaple roof towards	S460	0.0	Simple bar	Bar
76	28	11	exaple roof towards	S460	0.0	Simple bar	Bar
77	29	5	exaple roof towards	S460	0.0	Simple bar	Bar
78	29	6	exaple roof towards	S460	0.0	Simple bar	Bar
79	29	11	exaple roof towards	S460	0.0	Simple bar	Bar
80	29	12	exaple roof towards	S460	0.0	Simple bar	Bar
81	30	7	exaple roof towards	S460	0.0	Simple bar	Bar
82	30	8	exaple roof towards	S460	0.0	Simple bar	Bar
83	30	13	exaple roof towards	S460	0.0	Simple bar	Bar
84	30	14	exaple roof towards	S460	0.0	Simple bar	Bar
85	31	8	exaple roof towards	S460	0.0	Simple bar	Bar
86	31	9	exaple roof towards	S460	0.0	Simple bar	Bar
87	31	14	exaple roof towards	S460	0.0	Simple bar	Bar
88	31	15	exaple roof towards	S460	0.0	Simple bar	Bar
89	32	9	exaple roof towards	S460	0.0	Simple bar	Bar
90	32	10	exaple roof towards	S460	0.0	Simple bar	Bar
91	32	15	exaple roof towards	S460	0.0	Simple bar	Bar
92	32	16	exaple roof towards	S460	0.0	Simple bar	Bar
93	33	10	exaple roof towards	S460	0.0	Simple bar	Bar
94	33	11	exaple roof towards	S460	0.0	Simple bar	Bar
95	33	16	exaple roof towards	S460	0.0	Simple bar	Bar
96	33	17	exaple roof towards	S460	0.0	Simple bar	Bar
97	34	11	exaple roof towards	S460	0.0	Simple bar	Bar
98	34	12	exaple roof towards	S460	0.0	Simple bar	Bar
99	34	17	exaple roof towards	S460	0.0	Simple bar	Bar
100	34	18	exaple roof towards	S460	0.0	Simple bar	Bar
101	35	13	exaple roof towards	S460	0.0	Simple bar	Bar
102	35	14	exaple roof towards	S460	0.0	Simple bar	Bar
103	35	19	exaple roof towards	*S460*	0.0	Simple bar	Bar
104	35	20	exaple roof towards	S460	0.0	Simple bar	Bar
105	36	14	exaple roof towards	*S460*	0.0	Simple bar	Bar
106	36	15	exaple roof towards	S460	0.0	Simple bar	Bar
107	36	20	exaple roof towards	S460	0.0	Simple bar	Bar
108	36	21	exaple roof towards	*S460*	0.0	Simple bar	Bar
109	37	15	exaple roof towards	*S460*	0.0	Simple bar	Bar
110	37	16	exaple roof towards	*S460*	0.0	Simple bar	Bar
111	37	21	exaple roof towards	*S460*	0.0	Simple bar	Bar
112	37	22	exaple roof towards	*S460*	0.0	Simple bar	Bar
113	38	16	exaple roof towards	*S460*	0.0	Simple bar	Bar
114	38	17	exaple roof towards	S460	0.0	Simple bar	Bar
115	38	22	exaple roof towards	*S460*	0.0	Simple bar	Bar
116	38	23	exaple roof towards	*S460*	0.0	Simple bar	Bar
117	39	17	exaple roof towards	*S460*	0.0	Simple bar	Bar
118	39	18	exaple roof towards	*S460*	0.0	Simple bar	Bar
119	39	23	exaple roof towards	*S460*	0.0	Simple bar	Bar
120	39	24	exaple roof towards	*S460*	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	0.0	0.0	0.0	
2	1.000	0.500	0.0	
3	2.000	1.000	0.0	
4	3.000	1.500	0.0	
5	4.000	2.000	0.0	
6	5.000	2.500	0.0	
7	0.0	0.0	-1.000	
8	1.000	0.500	-1.000	
9	2.000	1.000	-1.000	
10	3.000	1.500	-1.000	
11	4.000	2.000	-1.000	
12	5.000	2.500	-1.000	
13	0.0	0.0	-2.000	
14	1.000	0.500	-2.000	
15	2.000	1.000	-2.000	
16	3.000	1.500	-2.000	
17	4.000	2.000	-2.000	
18	5.000	2.500	-2.000	
19	0.0	0.0	-3.000	
20	1.000	0.500	-3.000	
21	2.000	1.000	-3.000	
22	3.000	1.500	-3.000	
23	4.000	2.000	-3.000	
24	5.000	2.500	-3.000	
25	0.500	-1.000	-0.500	Pinned
26	1.500	-0.500	-0.500	
27	2.500	0.0	-0.500	
28	3.500	0.500	-0.500	
29	4.500	1.000	-0.500	Pinned
30	0.500	-1.000	-1.500	
31	1.500	-0.500	-1.500	
32	2.500	0.0	-1.500	
33	3.500	0.500	-1.500	
34	4.500	1.000	-1.500	
35	0.500	-1.000	-2.500	Pinned
36	1.500	-0.500	-2.500	
37	2.500	0.0	-2.500	
38	3.500	0.500	-2.500	
39	4.500	1.000	-2.500	Pinned

1.2CaseTwo: Curved roof

Node 61, Elements 200

	Section name	Bar list	AX (mm2)	AY (mm2)	AZ (mm2)	IX (mm4)	IY (mm4)	IZ (mm4)
	example Circular	o22 24to201	3199.923	2699.935	2699.935	629668.504	814834.252	814834.252

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
1	1	2	e Circular	S460	0.0	Simple bar	Bar
2	2	3	e Circular	S460	0.0	Simple bar	Bar
3	3	4	e Circular	S460	0.0	Simple bar	Bar
4	4	5	e Circular	S460	0.0	Simple bar	Bar
5	5	6	e Circular	S460	0.0	Simple bar	Bar
6	7	8	e Circular	S460	0.0	Simple bar	Bar
7	8	9	e Circular	S460	0.0	Simple bar	Bar
8	9	10	e Circular	S460	0.0	Simple bar	Bar
9	10	11	e Circular	S460	0.0	Simple bar	Bar
10	11	12	e Circular	S460	0.0	Simple bar	Bar
11	13	14	e Circular	S460	0.0	Simple bar	Bar
12	14	15	e Circular	S460	0.0	Simple bar	Bar
13	15	16	e Circular	S460	0.0	Simple bar	Bar
14	16	17	e Circular	S460	0.0	Simple bar	Bar
15	17	18	e Circular	S460	0.0	Simple bar	Bar
16	19	20	e Circular	S460	0.0	Simple bar	Bar
17	20	21	e Circular	S460	0.0	Simple bar	Bar
18	21	22	e Circular	S460	0.0	Simple bar	Bar
19	22	23	e Circular	S460	0.0	Simple bar	Bar
20	23	24	e Circular	S460	0.0	Simple bar	Bar
21	25	26	e Circular	S460	0.0	Simple bar	Bar
22	26	27	e Circular	S460	0.0	Simple bar	Bar
24	27	28	e Circular	S460	0.0	Simple bar	Bar
25	28	29	e Circular	S460	0.0	Simple bar	Bar
26	29	30	e Circular	S460	0.0	Simple bar	Bar
27	31	32	e Circular	S460	0.0	Simple bar	Bar
28	32	33	e Circular	S460	0.0	Simple bar	Bar
29	33	34	e Circular	S460	0.0	Simple bar	Bar
30	34	35	e Circular	S460	0.0	Simple bar	Bar
31	35	36	e Circular	S460	0.0	Simple bar	Bar
32	1	7	e Circular	S460	0.0	Simple bar	Bar
33	2	8	e Circular	S460	0.0	Simple bar	Bar
34	3	9	e Circular	S460	0.0	Simple bar	Bar
35	4	10	e Circular	S460	0.0	Simple bar	Bar
36	5	11	e Circular	S460	0.0	Simple bar	Bar
37	6	12	e Circular	S460	0.0	Simple bar	Bar
38	7	13	e Circular	S460	0.0	Simple bar	Bar
39	8	14	e Circular	S460	0.0	Simple bar	Bar
40	9	15	e Circular	S460	0.0	Simple bar	Bar
41	10	16	e Circular	S460	0.0	Simple bar	Bar
42	11	17	e Circular	S460	0.0	Simple bar	Bar
43	12	18	e Circular	S460	0.0	Simple bar	Bar
44	13	19	e Circular	S460	0.0	Simple bar	Bar
45	14	20	e Circular	S460	0.0	Simple bar	Bar
46	15	21	e Circular	S460	0.0	Simple bar	Bar
47	16	22	e Circular	S460	0.0	Simple bar	Bar
48	17	23	e Circular	S460	0.0	Simple bar	Bar
49	18	24	e Circular	S460	0.0	Simple bar	Bar
50	19	25	e Circular	S460	0.0	Simple bar	Bar
51	20	26	e Circular	S460	0.0	Simple bar	Bar
52	21	27	e Circular	S460	0.0	Simple bar	Bar
53	22	28	e Circular	S460	0.0	Simple bar	Bar
54	23	29	e Circular	S460	0.0	Simple bar	Bar
55	24	30	e Circular	S460	0.0	Simple bar	Bar
56	25	31	e Circular	S460	0.0	Simple bar	Bar
57	26	32	e Circular	S460	0.0	Simple bar	Bar
58	27	33	e Circular	S460	0.0	Simple bar	Bar

59	28	34	e Circular	S460	0.0	Simple bar	Bar
60	29	35	e Circular	S460	0.0	Simple bar	Bar
61	30	36	e Circular	S460	0.0	Simple bar	Bar
62	37	38	e Circular	S460	0.0	Simple bar	Bar
63	38	39	e Circular	S460	0.0	Simple bar	Bar
64	39	40	e Circular	S460	0.0	Simple bar	Bar
65	40	41	e Circular	S460	0.0	Simple bar	Bar
66	42	43	e Circular	S460	0.0	Simple bar	Bar
67	43	44	e Circular	S460	0.0	Simple bar	Bar
68	44	45	e Circular	S460	0.0	Simple bar	Bar
69	45	46	e Circular	S460	0.0	Simple bar	Bar
70	47	48	e Circular	S460	0.0	Simple bar	Bar
71	48	49	e Circular	S460	0.0	Simple bar	Bar
72	49	50	e Circular	S460	0.0	Simple bar	Bar
73	50	51	e Circular	S460	0.0	Simple bar	Bar
74	52	53	e Circular	S460	0.0	Simple bar	Bar
75	53	54	e Circular	S460	0.0	Simple bar	Bar
76	54	55	e Circular	S460	0.0	Simple bar	Bar
77	55	56	e Circular	S460	0.0	Simple bar	Bar
78	57	58	e Circular	S460	0.0	Simple bar	Bar
79	58	59	e Circular	S460	0.0	Simple bar	Bar
80	59	60	e Circular	S460	0.0	Simple bar	Bar
81	60	61	e Circular	S460	0.0	Simple bar	Bar
82	37	42	e Circular	S460	0.0	Simple bar	Bar
83	38	43	e Circular	S460	0.0	Simple bar	Bar
84	39	44	e Circular	S460	0.0	Simple bar	Bar
85	40	45	e Circular	S460	0.0	Simple bar	Bar
86	41	46	e Circular	S460	0.0	Simple bar	Bar
87	42	47	e Circular	S460	0.0	Simple bar	Bar
88	43	48	e Circular	S460	0.0	Simple bar	Bar
89	44	49	e Circular	S460	0.0	Simple bar	Bar
90	45	50	e Circular	S460	0.0	Simple bar	Bar
91	46	51	e Circular	S460	0.0	Simple bar	Bar
92	47	52	e Circular	S460	0.0	Simple bar	Bar
93	48	53	e Circular	S460	0.0	Simple bar	Bar
94	49	54	e Circular	S460	0.0	Simple bar	Bar
95	50	55	e Circular	S460	0.0	Simple bar	Bar
96	51	56	e Circular	S460	0.0	Simple bar	Bar
97	52	57	e Circular	S460	0.0	Simple bar	Bar
98	53	58	e Circular	S460	0.0	Simple bar	Bar
99	54	59	e Circular	S460	0.0	Simple bar	Bar
100	55	60	e Circular	S460	0.0	Simple bar	Bar
101	56	61	e Circular	S460	0.0	Simple bar	Bar
102	37	1	e Circular	S460	0.0	Simple bar	Bar
103	37	2	e Circular	S460	0.0	Simple bar	Bar
104	37	7	e Circular	S460	0.0	Simple bar	Bar
105	37	8	e Circular	S460	0.0	Simple bar	Bar
106	38	2	e Circular	S460	0.0	Simple bar	Bar
107	38	3	e Circular	S460	0.0	Simple bar	Bar
108	38	8	e Circular	S460	0.0	Simple bar	Bar
109	38	9	e Circular	S460	0.0	Simple bar	Bar
110	39	3	e Circular	S460	0.0	Simple bar	Bar
111	39	4	e Circular	S460	0.0	Simple bar	Bar
112	39	9	e Circular	S460	0.0	Simple bar	Bar
113	39	10	e Circular	S460	0.0	Simple bar	Bar
114	40	4	e Circular	S460	0.0	Simple bar	Bar
115	40	5	e Circular	S460	0.0	Simple bar	Bar
116	40	10	e Circular	S460	0.0	Simple bar	Bar
117	40	11	e Circular	S460	0.0	Simple bar	Bar
118	41	5	e Circular	S460	0.0	Simple bar	Bar
119	41	6	e Circular	S460	0.0	Simple bar	Bar
120	41	11	e Circular	S460	0.0	Simple bar	Bar

121	41	12	e Circular	S460	0.0	Simple bar	Bar
122	42	7	e Circular	S460	0.0	Simple bar	Bar
123	42	8	e Circular	S460	0.0	Simple bar	Bar
124	42	13	e Circular	S460	0.0	Simple bar	Bar
125	42	14	e Circular	S460	0.0	Simple bar	Bar
126	43	8	e Circular	S460	0.0	Simple bar	Bar
127	43	9	e Circular	S460	0.0	Simple bar	Bar
128	43	14	e Circular	S460	0.0	Simple bar	Bar
129	43	15	e Circular	S460	0.0	Simple bar	Bar
130	44	9	e Circular	S460	0.0	Simple bar	Bar
131	44	10	e Circular	S460	0.0	Simple bar	Bar
132	44	15	e Circular	S460	0.0	Simple bar	Bar
133	44	16	e Circular	S460	0.0	Simple bar	Bar
134	45	10	e Circular	S460	0.0	Simple bar	Bar
135	45	11	e Circular	S460	0.0	Simple bar	Bar
136	45	16	e Circular	S460	0.0	Simple bar	Bar
137	45	17	e Circular	S460	0.0	Simple bar	Bar
138	46	11	e Circular	S460	0.0	Simple bar	Bar
139	46	12	e Circular	S460	0.0	Simple bar	Bar
140	46	17	e Circular	S460	0.0	Simple bar	Bar
141	46	18	e Circular	S460	0.0	Simple bar	Bar
142	47	13	e Circular	S460	0.0	Simple bar	Bar
143	47	14	e Circular	S460	0.0	Simple bar	Bar
144	47	19	e Circular	S460	0.0	Simple bar	Bar
145	47	20	e Circular	S460	0.0	Simple bar	Bar
146	48	14	e Circular	S460	0.0	Simple bar	Bar
147	48	15	e Circular	S460	0.0	Simple bar	Bar
148	48	20	e Circular	S460	0.0	Simple bar	Bar
149	48	21	e Circular	S460	0.0	Simple bar	Bar
150	49	15	e Circular	S460	0.0	Simple bar	Bar
151	49	16	e Circular	S460	0.0	Simple bar	Bar
152	49	21	e Circular	S460	0.0	Simple bar	Bar
153	49	22	e Circular	S460	0.0	Simple bar	Bar
154	50	16	e Circular	S460	0.0	Simple bar	Bar
155	50	17	e Circular	S460	0.0	Simple bar	Bar
156	50	22	e Circular	S460	0.0	Simple bar	Bar
157	50	23	e Circular	S460	0.0	Simple bar	Bar
158	51	17	e Circular	S460	0.0	Simple bar	Bar
159	51	18	e Circular	S460	0.0	Simple bar	Bar
160	51	23	e Circular	S460	0.0	Simple bar	Bar
161	51	24	e Circular	S460	0.0	Simple bar	Bar
162	52	19	e Circular	S460	0.0	Simple bar	Bar
163	52	20	e Circular	S460	0.0	Simple bar	Bar
164	52	25	e Circular	S460	0.0	Simple bar	Bar
165	52	26	e Circular	S460	0.0	Simple bar	Bar
166	53	20	e Circular	S460	0.0	Simple bar	Bar
167	53	21	e Circular	S460	0.0	Simple bar	Bar
168	53	26	e Circular	S460	0.0	Simple bar	Bar
169	53	27	e Circular	S460	0.0	Simple bar	Bar
170	54	21	e Circular	S460	0.0	Simple bar	Bar
171	54	22	e Circular	S460	0.0	Simple bar	Bar
172	54	27	e Circular	S460	0.0	Simple bar	Bar
173	54	28	e Circular	S460	0.0	Simple bar	Bar
174	55	22	e Circular	S460	0.0	Simple bar	Bar
175	55	23	e Circular	S460	0.0	Simple bar	Bar
176	55	28	e Circular	S460	0.0	Simple bar	Bar
177	55	29	e Circular	S460	0.0	Simple bar	Bar
178	56	23	e Circular	S460	0.0	Simple bar	Bar
179	56	24	e Circular	S460	0.0	Simple bar	Bar
180	56	29	e Circular	S460	0.0	Simple bar	Bar

181	56	30	e Circular	*S460*	0.0	Simple bar	Bar
182	57	25	e Circular	*S460*	0.0	Simple bar	Bar
183	57	26	e Circular	*S460*	0.0	Simple bar	Bar
184	57	31	e Circular	*S460*	0.0	Simple bar	Bar
185	57	32	e Circular	*S460*	0.0	Simple bar	Bar
186	58	26	e Circular	*S460*	0.0	Simple bar	Bar
187	58	27	e Circular	*S460*	0.0	Simple bar	Bar
188	58	32	e Circular	*S460*	0.0	Simple bar	Bar
189	58	33	e Circular	*S460*	0.0	Simple bar	Bar
190	59	27	e Circular	*S460*	0.0	Simple bar	Bar
191	59	28	e Circular	*S460*	0.0	Simple bar	Bar
192	59	33	e Circular	*S460*	0.0	Simple bar	Bar
193	59	34	e Circular	*S460*	0.0	Simple bar	Bar
194	60	28	e Circular	*S460*	0.0	Simple bar	Bar
195	60	29	e Circular	*S460*	0.0	Simple bar	Bar
196	60	34	e Circular	*S460*	0.0	Simple bar	Bar
197	60	35	e Circular	*S460*	0.0	Simple bar	Bar
198	61	29	e Circular	*S460*	0.0	Simple bar	Bar
199	61	30	e Circular	*S460*	0.0	Simple bar	Bar
200	61	35	e Circular	*S460*	0.0	Simple bar	Bar
201	61	36	e Circular	*S460*	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	0.0	0.0	0.0	Pinned
2	4.000	2.000	0.0	
3	8.000	3.000	0.0	
4	12.000	3.500	0.0	
5	16.000	3.200	0.0	
6	20.000	3.000	0.0	Pinned
7	0.0	0.0	-2.000	Pinned
8	4.000	2.000	-2.000	
9	8.000	3.000	-2.000	
10	12.000	3.500	-2.000	
11	16.000	3.200	-2.000	
12	20.000	3.000	-2.000	Pinned
13	0.0	0.0	-4.000	Pinned
14	4.000	2.000	-4.000	
15	8.000	3.000	-4.000	
16	12.000	3.500	-4.000	
17	16.000	3.200	-4.000	
18	20.000	3.000	-4.000	Pinned
19	0.0	0.0	-6.000	Pinned
20	4.000	2.000	-6.000	
21	8.000	3.000	-6.000	
22	12.000	3.500	-6.000	
23	16.000	3.200	-6.000	
24	20.000	3.000	-6.000	Pinned
25	0.0	0.0	-8.000	Pinned
26	4.000	2.000	-8.000	
27	8.000	3.000	-8.000	
28	12.000	3.500	-8.000	
29	16.000	3.200	-8.000	
30	20.000	3.000	-8.000	Pinned
31	0.0	0.0	-10.000	Pinned
32	4.000	2.000	-10.000	
33	8.000	3.000	-10.000	
34	12.000	3.500	-10.000	
35	16.000	3.200	-10.000	
36	20.000	3.000	-10.000	Pinned
37	2.000	-1.000	-1.000	Pinned
38	6.000	1.000	-1.000	
39	10.000	2.000	-1.000	
40	14.000	2.500	-1.000	
41	18.000	2.200	-1.000	Pinned
42	2.000	-1.000	-3.000	Pinned
43	6.000	1.000	-3.000	
44	10.000	2.000	-3.000	
45	14.000	2.500	-3.000	
46	18.000	2.200	-3.000	Pinned
47	2.000	-1.000	-5.000	Pinned
48	6.000	1.000	-5.000	
49	10.000	2.000	-5.000	
50	14.000	2.500	-5.000	
51	18.000	2.200	-5.000	Pinned
52	2.000	-1.000	-7.000	Pinned
53	6.000	1.000	-7.000	
54	10.000	2.000	-7.000	
55	14.000	2.500	-7.000	
56	18.000	2.200	-7.000	Pinned
57	2.000	-1.000	-9.000	Pinned
58	6.000	1.000	-9.000	
59	10.000	2.000	-9.000	
60	14.000	2.500	-9.000	
61	18.000	2.200	-9.000	Pinned

1.3.1 Case Three: Star dome roof (a)

13 Nodes, 24 Elements.

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Section name	Bar list	AX (mm2)	AY (mm2)	AZ (mm2)	IX (mm4)	IY (mm4)	IZ (mm4)
example Circular	1to24	3199.923	2699.935	2699.935	629668.504	814834.252	814834.252

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
1	1	2	e Circular	S460	0.0	Simple bar	Bar
2	2	3	e Circular	S460	0.0	Simple bar	Bar
3	3	4	e Circular	S460	0.0	Simple bar	Bar
4	4	5	e Circular	S460	0.0	Simple bar	Bar
5	5	6	e Circular	S460	0.0	Simple bar	Bar
6	6	7	e Circular	S460	0.0	Simple bar	Bar
7	7	8	e Circular	S460	0.0	Simple bar	Bar
8	8	9	e Circular	S460	0.0	Simple bar	Bar
9	9	10	e Circular	S460	0.0	Simple bar	Bar
10	10	11	e Circular	S460	0.0	Simple bar	Bar
11	11	12	e Circular	S460	0.0	Simple bar	Bar
12	1	12	e Circular	S460	0.0	Simple bar	Bar
13	4	13	e Circular	S460	0.0	Simple bar	Bar
14	6	13	e Circular	S460	0.0	Simple bar	Bar
15	6	8	e Circular	S460	0.0	Simple bar	Bar
16	8	13	e Circular	S460	0.0	Simple bar	Bar
17	8	10	e Circular	S460	0.0	Simple bar	Bar
18	10	13	e Circular	S460	0.0	Simple bar	Bar
19	10	12	e Circular	S460	0.0	Simple bar	Bar
20	12	13	e Circular	S460	0.0	Simple bar	Bar
21	2	12	e Circular	S460	0.0	Simple bar	Bar
22	2	13	e Circular	S460	0.0	Simple bar	Bar
23	4	6	e Circular	S460	0.0	Simple bar	Bar
24	4	2	e Circular	S460	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	8.000	0.0	0.0	Pinned
2	11.000	2.000	3.000	
3	17.000	0.0	3.000	Pinned
4	13.000	2.000	8.000	
5	17.000	0.0	13.000	Pinned
6	11.000	2.000	13.000	
7	8.000	0.0	17.000	Pinned
8	6.000	2.000	13.000	
9	0.0	0.0	13.000	Pinned
10	3.000	2.000	8.000	
11	0.0	0.0	3.000	Pinned
12	6.000	2.000	3.000	
13	8.000	5.000	8.000	

1.3.2 Case Three: Star dome roof (b)

19 Nodes, 36 Elements.

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
1	1	2	example Circular	S460	0.0	Simple bar	Bar
2	2	3	example Circular	S460	0.0	Simple bar	Bar
3	3	4	example Circular	S460	0.0	Simple bar	Bar
4	4	5	example Circular	S460	0.0	Simple bar	Bar
5	5	6	example Circular	S460	0.0	Simple bar	Bar
6	6	7	example Circular	S460	0.0	Simple bar	Bar
7	7	8	example Circular	S460	0.0	Simple bar	Bar
8	8	9	example Circular	S460	0.0	Simple bar	Bar
9	9	10	example Circular	S460	0.0	Simple bar	Bar
10	10	11	example Circular	S460	0.0	Simple bar	Bar
11	11	12	example Circular	S460	0.0	Simple bar	Bar
12	1	12	example Circular	S460	0.0	Simple bar	Bar
13	4	17	example Circular	S460	0.0	Simple bar	Bar
14	6	16	example Circular	S460	0.0	Simple bar	Bar
15	6	8	example Circular	S460	0.0	Simple bar	Bar
16	8	15	example Circular	S460	0.0	Simple bar	Bar
17	8	10	example Circular	S460	0.0	Simple bar	Bar
18	10	14	example Circular	S460	0.0	Simple bar	Bar
19	10	12	example Circular	S460	0.0	Simple bar	Bar
20	12	19	example Circular	S460	0.0	Simple bar	Bar
21	2	12	example Circular	S460	0.0	Simple bar	Bar
22	2	18	example Circular	S460	0.0	Simple bar	Bar
23	4	6	example Circular	S460	0.0	Simple bar	Bar
24	4	2	example Circular	S460	0.0	Simple bar	Bar
25	17	13	example Circular	S460	0.0	Simple bar	Bar
26	18	13	example Circular	S460	0.0	Simple bar	Bar
27	14	13	example Circular	S460	0.0	Simple bar	Bar
28	15	13	example Circular	S460	0.0	Simple bar	Bar
29	16	13	example Circular	S460	0.0	Simple bar	Bar
31	14	15	example Circular	S460	0.0	Simple bar	Bar
32	15	16	example Circular	S460	0.0	Simple bar	Bar
33	16	17	example Circular	S460	0.0	Simple bar	Bar
34	17	18	example Circular	S460	0.0	Simple bar	Bar
35	18	19	example Circular	S460	0.0	Simple bar	Bar
36	19	14	example Circular	S460	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	8.000	0.0	0.0	Pinned
2	11.000	2.000	3.000	
3	17.000	0.0	3.000	Pinned
4	13.000	2.000	8.000	
5	17.000	0.0	13.000	Pinned
6	11.000	2.000	13.000	
7	8.000	0.0	17.000	Pinned
8	6.000	2.000	13.000	
9	0.0	0.0	13.000	Pinned
10	3.000	2.000	8.000	
11	0.0	0.0	3.000	Pinned
12	6.000	2.000	3.000	
13	8.000	5.000	8.000	
14	5.500	3.500	8.000	
15	7.000	3.500	10.500	
16	9.500	3.500	10.500	
17	10.500	3.500	8.000	
18	9.500	3.500	5.500	
19	7.000	3.500	5.500	

1.3.2 Case Three: Star dome roof (c)

27 Nodes, 43 Elements.

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
1	1	2	example Circular	S460	0.0	Simple bar	Bar
2	2	3	example Circular	S460	0.0	Simple bar	Bar
3	3	4	example Circular	S460	0.0	Simple bar	Bar
4	4	5	example Circular	S460	0.0	Simple bar	Bar
5	5	6	example Circular	S460	0.0	Simple bar	Bar
6	6	7	example Circular	S460	0.0	Simple bar	Bar
7	7	8	example Circular	S460	0.0	Simple bar	Bar
8	8	9	example Circular	S460	0.0	Simple bar	Bar
9	9	10	example Circular	S460	0.0	Simple bar	Bar
10	10	11	example Circular	S460	0.0	Simple bar	Bar
11	11	12	example Circular	S460	0.0	Simple bar	Bar
12	1	12	example Circular	S460	0.0	Simple bar	Bar
13	4	17	example Circular	S460	0.0	Simple bar	Bar
14	6	16	example Circular	S460	0.0	Simple bar	Bar
15	6	8	example Circular	S460	0.0	Simple bar	Bar
16	8	15	example Circular	S460	0.0	Simple bar	Bar
17	8	10	example Circular	S460	0.0	Simple bar	Bar
18	10	14	example Circular	S460	0.0	Simple bar	Bar
19	10	12	example Circular	S460	0.0	Simple bar	Bar
20	12	19	example Circular	S460	0.0	Simple bar	Bar
21	2	12	example Circular	S460	0.0	Simple bar	Bar
22	2	18	example Circular	S460	0.0	Simple bar	Bar
23	4	6	example Circular	S460	0.0	Simple bar	Bar
24	4	2	example Circular	S460	0.0	Simple bar	Bar
25	17	13	example Circular	S460	0.0	Simple bar	Bar
26	18	13	example Circular	S460	0.0	Simple bar	Bar
27	14	13	example Circular	S460	0.0	Simple bar	Bar
28	15	13	example Circular	S460	0.0	Simple bar	Bar
29	16	13	example Circular	S460	0.0	Simple bar	Bar
30	19	13	example Circular	S460	0.0	Simple bar	Bar
31	14	15	example Circular	S460	0.0	Simple bar	Bar
32	15	16	example Circular	S460	0.0	Simple bar	Bar
33	16	17	example Circular	S460	0.0	Simple bar	Bar
34	17	18	example Circular	S460	0.0	Simple bar	Bar
35	18	19	example Circular	S460	0.0	Simple bar	Bar
36	19	14	example Circular	S460	0.0	Simple bar	Bar
38	22	23	example Circular	S460	0.0	Simple bar	Bar
39	23	24	example Circular	S460	0.0	Simple bar	Bar
40	24	25	example Circular	S460	0.0	Simple bar	Bar
41	25	26	example Circular	S460	0.0	Simple bar	Bar
42	26	27	example Circular	S460	0.0	Simple bar	Bar
43	27	22	example Circular	S460	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	8.000	0.0	0.0	Pinned
2	11.000	2.000	3.000	
3	17.000	0.0	3.000	Pinned
4	13.000	2.000	8.000	
5	17.000	0.0	13.000	Pinned
6	11.000	2.000	13.000	
7	8.000	0.0	17.000	Pinned
8	6.000	2.000	13.000	
9	0.0	0.0	13.000	Pinned
10	3.000	2.000	8.000	
11	0.0	0.0	3.000	Pinned
12	6.000	2.000	3.000	
13	8.000	5.000	8.000	
14	5.500	3.500	8.000	
15	7.000	3.500	10.500	
16	9.500	3.500	10.500	
17	10.500	3.500	8.000	
18	9.500	3.500	5.500	
19	7.000	3.500	5.500	
22	6.500	2.750	11.750	
23	4.250	2.750	8.000	
24	6.500	2.750	4.250	
25	10.250	2.750	4.250	
26	11.750	2.750	8.000	
27	10.250	2.750	11.750	

1.4 Case Four: Circular dome roof

97 Nodes, 264 Elements.

	Section name	Bar list	AX (mm2)	AY (mm2)	AZ (mm2)	IX (mm4)	IY (mm4)	IZ (mm4)
	ahmed	53 255to275	3199.9233	2699.9353	2699.9353	29668.5037	14834.2518	14834.2518

Bar	Node 1	Node 2	Section	Material	Gamma (Deg)	Type	Structure object
2	1	2	ahmed	S275	0.0	Simple bar	Bar
3	2	3	ahmed	S275	0.0	Simple bar	Bar
4	3	4	ahmed	S275	0.0	Simple bar	Bar
5	4	5	ahmed	S275	0.0	Simple bar	Bar
6	5	6	ahmed	S275	0.0	Simple bar	Bar
7	6	7	ahmed	S275	0.0	Simple bar	Bar
8	7	8	ahmed	S275	0.0	Simple bar	Bar
9	8	9	ahmed	S275	0.0	Simple bar	Bar
10	9	10	ahmed	S275	0.0	Simple bar	Bar
11	10	11	ahmed	S275	0.0	Simple bar	Bar
12	11	12	ahmed	S275	0.0	Simple bar	Bar
13	12	13	ahmed	S275	0.0	Simple bar	Bar
14	13	14	ahmed	S275	0.0	Simple bar	Bar
15	14	15	ahmed	S275	0.0	Simple bar	Bar
16	15	16	ahmed	S275	0.0	Simple bar	Bar
17	16	17	ahmed	S275	0.0	Simple bar	Bar
18	17	18	ahmed	S275	0.0	Simple bar	Bar
19	18	19	ahmed	S275	0.0	Simple bar	Bar
20	19	20	ahmed	S275	0.0	Simple bar	Bar
21	20	21	ahmed	S275	0.0	Simple bar	Bar
22	21	22	ahmed	S275	0.0	Simple bar	Bar
23	22	23	ahmed	S275	0.0	Simple bar	Bar
24	23	24	ahmed	S275	0.0	Simple bar	Bar
25	24	1	ahmed	S275	0.0	Simple bar	Bar
26	25	26	ahmed	S275	0.0	Simple bar	Bar
27	26	27	ahmed	S275	0.0	Simple bar	Bar
28	27	28	ahmed	S275	0.0	Simple bar	Bar
29	28	29	ahmed	S275	0.0	Simple bar	Bar
30	29	30	ahmed	S275	0.0	Simple bar	Bar
31	30	31	ahmed	S275	0.0	Simple bar	Bar
32	31	32	ahmed	S275	0.0	Simple bar	Bar
33	32	33	ahmed	S275	0.0	Simple bar	Bar
34	33	34	ahmed	S275	0.0	Simple bar	Bar
35	34	35	ahmed	S275	0.0	Simple bar	Bar
36	35	36	ahmed	S275	0.0	Simple bar	Bar
37	36	37	ahmed	S275	0.0	Simple bar	Bar
38	37	38	ahmed	S275	0.0	Simple bar	Bar
39	38	39	ahmed	S275	0.0	Simple bar	Bar
40	39	40	ahmed	S275	0.0	Simple bar	Bar
41	40	41	ahmed	S275	0.0	Simple bar	Bar
42	41	42	ahmed	S275	0.0	Simple bar	Bar
43	42	43	ahmed	S275	0.0	Simple bar	Bar
44	43	44	ahmed	S275	0.0	Simple bar	Bar
45	44	45	ahmed	S275	0.0	Simple bar	Bar
46	45	46	ahmed	S275	0.0	Simple bar	Bar
47	46	47	ahmed	S275	0.0	Simple bar	Bar
48	47	48	ahmed	S275	0.0	Simple bar	Bar
49	48	25	ahmed	S275	0.0	Simple bar	Bar
50	49	50	ahmed	S275	0.0	Simple bar	Bar

51	50	51	ahmed	S275	0.0	Simple bar	Bar
52	51	52	ahmed	S275	0.0	Simple bar	Bar
53	52	53	ahmed	S275	0.0	Simple bar	Bar
54	53	54	ahmed	S275	0.0	Simple bar	Bar
55	54	55	ahmed	S275	0.0	Simple bar	Bar
56	55	56	ahmed	S275	0.0	Simple bar	Bar
57	56	57	ahmed	S275	0.0	Simple bar	Bar
58	57	58	ahmed	S275	0.0	Simple bar	Bar
59	58	59	ahmed	S275	0.0	Simple bar	Bar
60	59	60	ahmed	S275	0.0	Simple bar	Bar
61	60	61	ahmed	S275	0.0	Simple bar	Bar
62	61	62	ahmed	S275	0.0	Simple bar	Bar
63	62	63	ahmed	S275	0.0	Simple bar	Bar
64	63	64	ahmed	S275	0.0	Simple bar	Bar
65	64	65	ahmed	S275	0.0	Simple bar	Bar
66	65	66	ahmed	S275	0.0	Simple bar	Bar
67	66	67	ahmed	S275	0.0	Simple bar	Bar
68	67	68	ahmed	S275	0.0	Simple bar	Bar
69	68	69	ahmed	S275	0.0	Simple bar	Bar
70	69	70	ahmed	S275	0.0	Simple bar	Bar
71	70	71	ahmed	S275	0.0	Simple bar	Bar
72	71	72	ahmed	S275	0.0	Simple bar	Bar
73	72	49	ahmed	S275	0.0	Simple bar	Bar
74	73	74	ahmed	S275	0.0	Simple bar	Bar
75	74	75	ahmed	S275	0.0	Simple bar	Bar
76	75	76	ahmed	S275	0.0	Simple bar	Bar
77	76	77	ahmed	S275	0.0	Simple bar	Bar
78	77	78	ahmed	S275	0.0	Simple bar	Bar
79	78	79	ahmed	S275	0.0	Simple bar	Bar
80	79	80	ahmed	S275	0.0	Simple bar	Bar
81	80	81	ahmed	S275	0.0	Simple bar	Bar
82	81	82	ahmed	S275	0.0	Simple bar	Bar
83	82	83	ahmed	S275	0.0	Simple bar	Bar
84	83	84	ahmed	S275	0.0	Simple bar	Bar
85	84	85	ahmed	S275	0.0	Simple bar	Bar
86	85	86	ahmed	S275	0.0	Simple bar	Bar
87	86	87	ahmed	S275	0.0	Simple bar	Bar
88	87	88	ahmed	S275	0.0	Simple bar	Bar
89	88	89	ahmed	S275	0.0	Simple bar	Bar
90	89	90	ahmed	S275	0.0	Simple bar	Bar
91	90	91	ahmed	S275	0.0	Simple bar	Bar
92	91	92	ahmed	S275	0.0	Simple bar	Bar
93	92	93	ahmed	S275	0.0	Simple bar	Bar
94	93	94	ahmed	S275	0.0	Simple bar	Bar
95	94	95	ahmed	S275	0.0	Simple bar	Bar
96	95	96	ahmed	S275	0.0	Simple bar	Bar
98	1	25	ahmed	S275	0.0	Simple bar	Bar
99	25	49	ahmed	S275	0.0	Simple bar	Bar
100	49	73	ahmed	S275	0.0	Simple bar	Bar
101	73	97	ahmed	S275	0.0	Simple bar	Bar
102	2	26	ahmed	S275	0.0	Simple bar	Bar
103	26	50	ahmed	S275	0.0	Simple bar	Bar
104	50	74	ahmed	S275	0.0	Simple bar	Bar
105	74	97	ahmed	S275	0.0	Simple bar	Bar
106	3	27	ahmed	S275	0.0	Simple bar	Bar
107	27	51	ahmed	S275	0.0	Simple bar	Bar
108	51	75	ahmed	S275	0.0	Simple bar	Bar
109	75	97	ahmed	S275	0.0	Simple bar	Bar
110	4	28	ahmed	S275	0.0	Simple bar	Bar
111	96	73	ahmed	S275	0.0	Simple bar	Bar
112	28	52	ahmed	S275	0.0	Simple bar	Bar

113	52	76	ahmed	S275	0.0	Simple bar	Bar
114	76	97	ahmed	S275	0.0	Simple bar	Bar
115	5	29	ahmed	S275	0.0	Simple bar	Bar
116	29	53	ahmed	S275	0.0	Simple bar	Bar
117	53	77	ahmed	S275	0.0	Simple bar	Bar
118	77	97	ahmed	S275	0.0	Simple bar	Bar
119	6	30	ahmed	S275	0.0	Simple bar	Bar
120	30	54	ahmed	S275	0.0	Simple bar	Bar
121	54	78	ahmed	S275	0.0	Simple bar	Bar
122	78	97	ahmed	S275	0.0	Simple bar	Bar
123	7	31	ahmed	S275	0.0	Simple bar	Bar
124	31	55	ahmed	S275	0.0	Simple bar	Bar
125	55	79	ahmed	S275	0.0	Simple bar	Bar
127	79	97	ahmed	S275	0.0	Simple bar	Bar
128	8	32	ahmed	S275	0.0	Simple bar	Bar
129	32	56	ahmed	S275	0.0	Simple bar	Bar
130	56	80	ahmed	S275	0.0	Simple bar	Bar
131	80	97	ahmed	S275	0.0	Simple bar	Bar
132	9	33	ahmed	S275	0.0	Simple bar	Bar
133	33	57	ahmed	S275	0.0	Simple bar	Bar
134	57	81	ahmed	S275	0.0	Simple bar	Bar
136	81	97	ahmed	S275	0.0	Simple bar	Bar
137	10	34	ahmed	S275	0.0	Simple bar	Bar
138	34	58	ahmed	S275	0.0	Simple bar	Bar
139	58	82	ahmed	S275	0.0	Simple bar	Bar
140	82	97	ahmed	S275	0.0	Simple bar	Bar
141	11	35	ahmed	S275	0.0	Simple bar	Bar
142	35	59	ahmed	S275	0.0	Simple bar	Bar
143	59	83	ahmed	S275	0.0	Simple bar	Bar
144	83	97	ahmed	S275	0.0	Simple bar	Bar
145	12	36	ahmed	S275	0.0	Simple bar	Bar
146	36	60	ahmed	S275	0.0	Simple bar	Bar
147	60	84	ahmed	S275	0.0	Simple bar	Bar
148	84	97	ahmed	S275	0.0	Simple bar	Bar
149	13	37	ahmed	S275	0.0	Simple bar	Bar
150	37	61	ahmed	S275	0.0	Simple bar	Bar
151	61	85	ahmed	S275	0.0	Simple bar	Bar
152	85	97	ahmed	S275	0.0	Simple bar	Bar
153	14	38	ahmed	S275	0.0	Simple bar	Bar
154	38	62	ahmed	S275	0.0	Simple bar	Bar
155	62	86	ahmed	S275	0.0	Simple bar	Bar
156	86	97	ahmed	S275	0.0	Simple bar	Bar
157	15	39	ahmed	S275	0.0	Simple bar	Bar
159	39	63	ahmed	S275	0.0	Simple bar	Bar
160	63	87	ahmed	S275	0.0	Simple bar	Bar
161	87	97	ahmed	S275	0.0	Simple bar	Bar
162	16	40	ahmed	S275	0.0	Simple bar	Bar
163	40	64	ahmed	S275	0.0	Simple bar	Bar
164	64	88	ahmed	S275	0.0	Simple bar	Bar
165	88	97	ahmed	S275	0.0	Simple bar	Bar
166	17	41	ahmed	S275	0.0	Simple bar	Bar
167	41	65	ahmed	S275	0.0	Simple bar	Bar
168	65	89	ahmed	S275	0.0	Simple bar	Bar
169	89	97	ahmed	S275	0.0	Simple bar	Bar
170	18	42	ahmed	S275	0.0	Simple bar	Bar
171	42	66	ahmed	S275	0.0	Simple bar	Bar
172	66	90	ahmed	S275	0.0	Simple bar	Bar
173	90	97	ahmed	S275	0.0	Simple bar	Bar
174	19	43	ahmed	S275	0.0	Simple bar	Bar
175	43	67	ahmed	S275	0.0	Simple bar	Bar
176	67	91	ahmed	S275	0.0	Simple bar	Bar
177	91	97	ahmed	S275	0.0	Simple bar	Bar
178	20	44	ahmed	S275	0.0	Simple bar	Bar
179	44	68	ahmed	S275	0.0	Simple bar	Bar
180	68	92	ahmed	S275	0.0	Simple bar	Bar
181	92	97	ahmed	S275	0.0	Simple bar	Bar

182	21	45	ahmed	S275	0.0	Simple bar	Bar
183	45	69	ahmed	S275	0.0	Simple bar	Bar
185	69	93	ahmed	S275	0.0	Simple bar	Bar
186	93	97	ahmed	S275	0.0	Simple bar	Bar
187	22	46	ahmed	S275	0.0	Simple bar	Bar
188	46	70	ahmed	S275	0.0	Simple bar	Bar
189	70	94	ahmed	S275	0.0	Simple bar	Bar
190	94	97	ahmed	S275	0.0	Simple bar	Bar
191	23	47	ahmed	S275	0.0	Simple bar	Bar
192	47	71	ahmed	S275	0.0	Simple bar	Bar
193	71	95	ahmed	S275	0.0	Simple bar	Bar
194	95	97	ahmed	S275	0.0	Simple bar	Bar
195	24	48	ahmed	S275	0.0	Simple bar	Bar
196	48	72	ahmed	S275	0.0	Simple bar	Bar
197	72	96	ahmed	S275	0.0	Simple bar	Bar
198	96	97	ahmed	S275	0.0	Simple bar	Bar
199	1	26	ahmed	S275	0.0	Simple bar	Bar
200	25	50	ahmed	S275	0.0	Simple bar	Bar
202	49	74	ahmed	S275	0.0	Simple bar	Bar
203	2	27	ahmed	S275	0.0	Simple bar	Bar
204	26	51	ahmed	S275	0.0	Simple bar	Bar
205	50	75	ahmed	S275	0.0	Simple bar	Bar
206	3	28	ahmed	S275	0.0	Simple bar	Bar
207	27	52	ahmed	S275	0.0	Simple bar	Bar
208	51	76	ahmed	S275	0.0	Simple bar	Bar
209	4	29	ahmed	S275	0.0	Simple bar	Bar
210	28	53	ahmed	S275	0.0	Simple bar	Bar
212	52	77	ahmed	S275	0.0	Simple bar	Bar
213	5	30	ahmed	S275	0.0	Simple bar	Bar
214	29	54	ahmed	S275	0.0	Simple bar	Bar
215	53	78	ahmed	S275	0.0	Simple bar	Bar
216	6	31	ahmed	S275	0.0	Simple bar	Bar
217	30	55	ahmed	S275	0.0	Simple bar	Bar
219	7	32	ahmed	S275	0.0	Simple bar	Bar
220	31	56	ahmed	S275	0.0	Simple bar	Bar
221	55	80	ahmed	S275	0.0	Simple bar	Bar
222	54	79	ahmed	S275	0.0	Simple bar	Bar
223	8	33	ahmed	S275	0.0	Simple bar	Bar
224	32	57	ahmed	S275	0.0	Simple bar	Bar
225	56	81	ahmed	S275	0.0	Simple bar	Bar
226	9	34	ahmed	S275	0.0	Simple bar	Bar
227	33	58	ahmed	S275	0.0	Simple bar	Bar
228	57	82	ahmed	S275	0.0	Simple bar	Bar
229	10	35	ahmed	S275	0.0	Simple bar	Bar
230	34	59	ahmed	S275	0.0	Simple bar	Bar
231	58	83	ahmed	S275	0.0	Simple bar	Bar
232	11	36	ahmed	S275	0.0	Simple bar	Bar
233	35	60	ahmed	S275	0.0	Simple bar	Bar
234	59	84	ahmed	S275	0.0	Simple bar	Bar
235	12	37	ahmed	S275	0.0	Simple bar	Bar
236	36	61	ahmed	S275	0.0	Simple bar	Bar
238	60	85	ahmed	S275	0.0	Simple bar	Bar
239	13	38	ahmed	S275	0.0	Simple bar	Bar
240	37	62	ahmed	S275	0.0	Simple bar	Bar
241	61	86	ahmed	S275	0.0	Simple bar	Bar
242	14	39	ahmed	S275	0.0	Simple bar	Bar
243	38	63	ahmed	S275	0.0	Simple bar	Bar
244	62	87	ahmed	S275	0.0	Simple bar	Bar
245	15	40	ahmed	S275	0.0	Simple bar	Bar
246	39	64	ahmed	S275	0.0	Simple bar	Bar
247	63	88	ahmed	S275	0.0	Simple bar	Bar
248	16	41	ahmed	S275	0.0	Simple bar	Bar
249	40	65	ahmed	S275	0.0	Simple bar	Bar
250	64	89	ahmed	S275	0.0	Simple bar	Bar
251	17	42	ahmed	S275	0.0	Simple bar	Bar
252	41	66	ahmed	S275	0.0	Simple bar	Bar

253	65	90	ahmed	S275	0.0	Simple bar	Bar
255	18	43	ahmed	S275	0.0	Simple bar	Bar
256	42	67	ahmed	S275	0.0	Simple bar	Bar
257	66	91	ahmed	S275	0.0	Simple bar	Bar
258	19	44	ahmed	S275	0.0	Simple bar	Bar
259	43	68	ahmed	S275	0.0	Simple bar	Bar
260	67	92	ahmed	S275	0.0	Simple bar	Bar
261	20	45	ahmed	S275	0.0	Simple bar	Bar
262	44	69	ahmed	S275	0.0	Simple bar	Bar
263	68	93	ahmed	S275	0.0	Simple bar	Bar
264	21	46	ahmed	S275	0.0	Simple bar	Bar
265	45	70	ahmed	S275	0.0	Simple bar	Bar
266	69	94	ahmed	S275	0.0	Simple bar	Bar
267	22	47	ahmed	S275	0.0	Simple bar	Bar
268	46	71	ahmed	S275	0.0	Simple bar	Bar
269	70	95	ahmed	S275	0.0	Simple bar	Bar
270	23	48	ahmed	S275	0.0	Simple bar	Bar
271	47	72	ahmed	S275	0.0	Simple bar	Bar
272	71	96	ahmed	S275	0.0	Simple bar	Bar
273	24	25	ahmed	S275	0.0	Simple bar	Bar
274	48	49	ahmed	S275	0.0	Simple bar	Bar
275	72	73	ahmed	S275	0.0	Simple bar	Bar

Node	X (m)	Y (m)	Z (m)	Support
1	22.9000	0.0	0.0	Pinned
2	22.1197	0.0	-5.9270	Pinned
3	19.8320	0.0	-11.4500	Pinned
4	16.1927	0.0	-16.1927	Pinned
5	11.4500	0.0	-19.8320	Pinned
6	5.9270	0.0	-22.1197	Pinned
7	0.0	0.0	-22.9000	Pinned
8	-5.9270	0.0	-22.1197	Pinned
9	-11.4500	0.0	-19.8320	Pinned
10	-16.1927	0.0	-16.1927	Pinned
11	-19.8320	0.0	-11.4500	Pinned
12	-22.1197	0.0	-5.9270	Pinned
13	-22.9000	0.0	0.0	Pinned
14	-22.1197	0.0	5.9270	Pinned
15	-19.8320	0.0	11.4500	Pinned
16	-16.1927	0.0	16.1927	Pinned
17	-11.4500	0.0	19.8320	Pinned
18	-5.9270	0.0	22.1197	Pinned
19	0.0	0.0	22.9000	Pinned
20	5.9270	0.0	22.1197	Pinned
21	11.4500	0.0	19.8320	Pinned
22	16.1927	0.0	16.1927	Pinned
23	19.8320	0.0	11.4500	Pinned
24	22.1197	0.0	5.9270	Pinned
25	21.3700	1.7900	0.0	
26	20.6418	1.7900	-5.5310	
27	18.5070	1.7900	-10.6850	
28	15.1109	1.7900	-15.1109	
29	10.6850	1.7900	-18.5070	
30	5.5310	1.7900	-20.6418	
31	0.0	1.7900	-21.3700	
32	-5.5310	1.7900	-20.6418	
33	-10.6850	1.7900	-18.5070	
34	-15.1109	1.7900	-15.1109	
35	-18.5070	1.7900	-11.6850	
36	-20.6418	1.7900	-5.5310	
37	-21.3700	1.7900	0.0	
38	-20.6418	1.7900	5.5310	
39	-18.5070	1.7900	10.6850	
40	-15.1109	1.7900	15.1109	
41	-10.6850	1.7900	18.5070	
42	-5.5310	1.7900	20.6418	
43	0.0	1.7900	21.3700	
44	5.5310	1.7900	20.6418	
45	10.6850	1.7900	18.5070	
46	15.1109	1.7900	15.1109	
47	18.5070	1.7900	10.6850	
48	20.6418	1.7900	5.5310	
49	16.4100	3.2600	0.0	
50	15.8508	3.2600	-4.2472	
51	14.2115	3.2600	-8.2050	
52	11.6036	3.2600	-11.6036	
53	8.2050	3.2600	-14.2115	
54	4.2427	3.2600	-15.8508	
55	0.0	3.2600	-16.4100	
56	-4.2472	3.2600	-15.8508	
57	-8.2050	3.2600	-14.2115	
58	-11.6036	3.2600	-11.6036	
59	-14.2115	3.2600	-8.2050	
60	-15.8508	3.2600	-4.2472	
61	-16.4100	3.2600	0.0	
62	-15.8508	3.2600	4.2472	

63	-14.2115	3.2600	8.2050	
64	-11.6036	3.2600	11.6036	
65	-8.2050	3.2600	14.2115	
66	-4.2472	3.2600	15.8508	
67	0.0	3.2600	16.4100	
68	4.2472	3.2600	15.8508	
69	8.2050	3.2600	14.2115	
70	11.6036	3.2600	11.6036	
71	14.2115	3.2600	8.2050	
72	15.8508	3.2600	4.2472	
73	8.7000	4.2700	0.0	
74	8.4036	4.2700	-2.2517	
75	7.5344	4.2700	-4.3500	
76	6.1518	4.2700	-6.1518	
77	4.3500	4.2700	-7.5344	
78	2.2517	4.2700	-8.4036	
79	0.0	4.2700	-8.7000	
80	-2.2517	4.2700	-8.4036	
81	-4.3500	4.2700	-7.5344	
82	-6.1518	4.2700	-6.1518	
83	-7.5344	4.2700	-4.3500	
84	-8.4036	4.2700	-2.2517	
85	-8.7000	4.2700	0.0	
86	-8.4036	4.2700	2.2517	
87	-7.5344	4.2700	4.3500	
88	-6.1518	4.2700	6.1518	
89	-4.3500	4.2700	7.5344	
90	-2.2517	4.2700	8.4036	
91	0.0	4.2700	8.7000	
92	2.2517	4.2700	8.4036	
93	4.3500	4.2700	7.5344	
94	6.1518	4.2700	6.1518	
95	7.5344	4.2700	4.3500	
96	8.4036	4.2700	2.2517	
97	0.0	4.5800	0.0	