ANALYSIS AND DESIGN
OF
INDOOR SPORTS STADIUM

By

Vaghasia Prashant B.
(05MCL016)

DEPARTMENT OF CIVIL ENGINEERING
Ahmedabad 382481
May 2007

ANALYSIS AND DESIGN
OF
INDOOR SPORTS STADIUM

Major Project

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Civil Engineering
(Computer Aided Structural Analysis & Design)

By

Vaghasia Prashant B.
(05MCL016)

Guide
Mr. Jayant Lakhlani

DEPARTMENT OF CIVIL ENGINEERING
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CERTIFICATE

This is to certify that the Major Project entitled "Analysis and Design of Indoor Sports Stadium" submitted by Mr. Vaghasia Prashant B. (05MCL016) , towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University of Science and Technology, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

Mr. Jayant Lakhlani
Guide,
Structural Consultant,
Rajkot.

Dr. P. H. Shah
Professor and Head,
Department of Civil Engineering,
Institute of Technology,
Nirma University,
Ahmedabad

Prof. A. B. Patel
Director,
Institute of Technology,
Nirma University,
Ahmedabad

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Examiner

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Examiner

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Date of Examination

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Vaghasia Prashant B.
Roll No.05 MCL 016

ABSTRACT

Indoor stadium is a typical structure that comes under the category of structures with large span column free area. A modern indoor sports stadium is a place or venue for sports, concerts or other events, consisting of a field or stage completely surrounded by a structure designed to allow spectators to stand or sit to view the event. Indoor sports stadium should be designed to satisfy all criteria regarding economy, safety, serviceability and esthetics.

To cover large span column free area there are many structural systems like cable suspended roof structures, single and multilayer grids, braced folded structures, braced domes, Stressed skin systems, tensile membrane structures and tensegritic structures. First three systems I have considered for detailed study.

The objective of the present study is comparison of cable suspended roof structure (single and double layer) system, double layer grid (square on square offset-cornice type) system and braced barrel vault (lamella type) system in context of their cost aspect.

This study is carried out with help of "STAAD-Pro 2005" to obtain accurate analytical results. It is essential to choose proper modeling, loading and support conditions. To check the applicability of software approximate analysis is carried out.

For single cable structure and double cable structure three different types of modeling aspects have been considered.

1. Cable is made of small straight cable elements.
2. Cable is made of only one cable element.
3. Cable is made of small straight beam element.

From the results, 3rd and 1st alternative of modeling proves compatible with approximate analysis for single cable suspended structure and double cable suspended structure respectively. For double layer grid, girder analogy method gives much closer results to exact analysis.

As such space structural systems are light weight structures compared to conventional structural systems. So static and dynamic wind analysis and static seismic analysis carried out. Different load combination is adopted as per Indian standards for the analysis of structure. Here, different types of connections is developed for different structural systems like cable-strut, cable-column (hinge connection), cable to ground, Mero node connectors, Steel tube to column, RHS to RHS, RHS to concrete column, sitting gallery, beam column junctions etc.

Comparative analysis of all three structural systems is carried out and shown for area of 40 m X 60 m.

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ABBREVIATION, NOTATION AND NOMENCLATURE

a:	Width of grid
$a1$:	Grid module
B:	Damping coefficient
b:	Width of beam
BBV:	Braced barrel vault
BC:	Bottom cable
C_y:	Lateral correlation constant
C_z:	Longitudinal correlation constant
D:	Depth of grid in m
d:	Depth of beam
DLG:	Double layer grid
E:	Modulus of elasticity
$F1$:	Factor for long span
$F2$:	Factor for short span
f_n:	Natural frequency
g_f :	Peak factor
I:	Moment of Inertia
L:	Length of beam
$L_{(h)}$:	A measure of turbulence scale
M:	Bending moment
M_{max}:	Maximum bending moment
N:	Integer value i.e. 1, 2, 3…
n:	Top chord module dimension in m
$P1$:	Maximum top and bottom chord forces parallel to sides A and B
$P2$:	Maximum top and bottom chord forces parallel to sides C and D
r:	Roughness factor
RHS:	Rectangular hollow section
S:	Size reduction factor
$\frac{SE}{\beta}$:	Measure of the resonant component of the fluctuating wind load
T:	Tension in cable
T:	Total load on grid in tonne
TC:	Top cable

W:	Uniformly distributed load in kN/m.
W_t:	Total factored load
W_x:	Total load in X-direction
W_y:	Total load in Y-direction
q:	Uniformly distributed load
$\dot{\alpha}$:	Rectangularity ratio
ρ:	Density of material

1. INTRODUCTION

1.1 GENERAL

Indoor sports stadiums like many other civil engineering structures are being pushed to their limits in terms of slenderness and structural efficiency. Indoor sports stadium structure should be designed for optimum balance between economy, safety, serviceability and esthetics aspects.

Indoor sport stadium is the structure where large spaces uninterrupted by structural members are needed to accommodate for certain activities, where it is important for visual connection to be established within the space with minimum distractions. So basically, Indoor sport stadium is the large span structure or large column free structure, which can be loosely defined as buildings which enclose large area without any intermediate supports. [16]

1.2 HISTORIC DEVELOPMENTS

A journey through the history of development of structural engineering would indicate a strong relationship between human need, development of conceptual solutions, analytical methods, materials and technology. Space structures are no exception. It will also be seen that nature often indicates new solutions. As an example, the large quantities of vines in the plants and creepers have suggested the use of rope in the use of suspended structures and the spider's web may have developed the ideas of 'tension' nets or membranes. [17]

The word stadium originates from the Greek "stadion", literally a (place where people) stand. The oldest known stadium is the one in Olympia, in western Peloponnesus, Greece, where the Olympic games of antiquity were held since 776 BC.

The principle of using tensioned cables in the construction of roofs was first used in A.D. 70, when the 189X156 m roman colosseum was constructed. But after this roof there was little progress in this field till 1950. The concept of cable applied to roof structures was developed from the suspension bridges. Cables have been used for suspension bridges for more than 100 years. However, this principal of suspension has been applied in the supporting of roofs and other members of buildings in the past 40 years. There is a sizable number of space structures for roofs that have come up in the past fifty years In the modern context, pioneering efforts to develop space structures can be credited to European engineers and to the Germans in particular (where names such as Frei Otto and Jorg Schlaich), with the lead taken in a big way thereafter in Japan and U.S.A. The real developments in the analysis, design and construction of cable roofs have occurred only after the Raleigh arena, designed by Nowicki, was built in the United States in 1953. [3]

The real developments of space frames took place after the book written by Leipzig under the title "Theory of lattice systems" in 1880. Alexander Graham Bell has carried out too many experiments with prefabricated multi-layered space framed in 1907. R.le Ricolais of the University of Pennsylvania, U.S.A. carried out detailed studies on the skeletal configurations of certain natural forms like sea fauna and algae. The idea of grid applied to roof structure was grown from nature. In 1940, an attention towards space frames carried out by Le Ricolais, after seeing the bone skeletons of "*Radia tuscaretta globosa*". [2]

The concept of braced barrel vault applied to roof structures was developed from the large cylindrical shape structures. Bricks and stones have been used for barrel vaults since many years. A logical improvement was the introduction of iron bars in the nineteenth centaury to have great influence on the construction of roof structures of considerable span. The first braced barrel vaults was constructed in 1809-11 of a 40 m clear span ribbed iron dome in Paris. The best example is the famous iron barrel vault designed by Joseph Paxton in 1851 in London. [7]

1.3 NEED OF LARGE SPAN STRUCTURES

For large span structures, traditional beam column system is not very effective. The bending moment increases substantially with the beam's span, thus requiring the beam's cross section to increase in the same order of magnitude. This can be easily illustrated mathematically through this following rectangular beam.

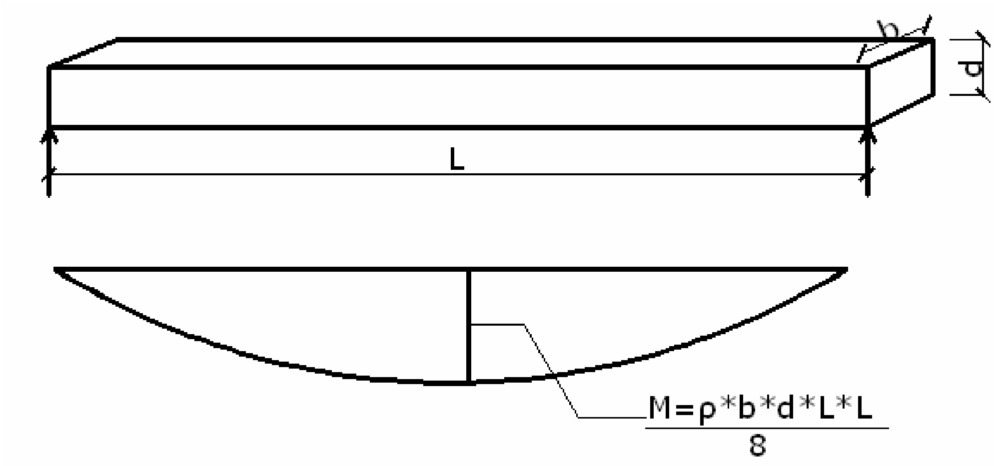


Figure 1.1 Bending in rectangular beam

For any beam, Basic equation of moment for simply supported beam is

$$\text{Bending Moment } M = \frac{WL^2}{8} \qquad \text{. . . (1.1)}$$

$$\text{Deflection, } \delta = \frac{WL^3}{EI} \qquad \text{. . . (1.2)}$$

Equation (1.1) shows that moment is directly proportional to square of length i.e. span of the beam, hence as span increases moment increases. Equation (1.2) shows as span increases deflection, which is directly proportional to the cube of the length, increases. So to overcome that moment again depth (d) is increasing. With this increase in depth, the dead load of the beam increases accordingly, applying on itself a proportional increase in bending moment, thus requiring an even deeper beam to resist the moment. As we increase the depth then the esthetics as well as economy criteria goes away while safety and serviceability criteria has a big question mark. This shows that with increasing span, solid beams become more and more clumsy, with their dead load eating away strength, making it unsuitable to span a greater length.

The failure of the beam for large span use demonstrates the ineffectiveness of flexure to resist load in this particular application. Therefore, many of the solutions derived for large span system explore the different ways of supporting loads without the need of bending. Some of these solutions include the truss system, whose elements are only subjected to axial stresses, shell structure, which if designed well could carry forces by pure compression and cable system, that resist load only through tension. In addition to the absence of bending, cables are light and have a high strength to weight ratio. Small members could therefore be used in very large span. [4]

1.4 STADIUM PRINCIPLES

There are six general principles pertaining to stadium construction.

i) Contents and functions:

First, it is important to develop a relationship between a stadium, sports, and the expectations of the audience. In order to achieve this, several critical aspects must be well thought out and properly integrated in planning phases. These includes the steel or reinforced concrete frames, tiers, galleries, staircases, roofs, tracks, locker rooms, press services(radio or television), conference rooms etc.

ii) Symmetry and differences:

Second, the stadium is generally symmetric with the conscious aim to repeat a similar representation of both horizontal and vertical views.

iii) Syntax of the stadium:

Third, the overall desired style and look of the stadium is important to consider. Understanding each of the separate critical aspects identified in the first guideline and deciding how they will be placed together is instrumental in determining the overall style of the stadium.

iv) Structural expressionism:

Fourth, one thinks of the range between historic styles to exciting experimental designs. Frames, pillars, roofs, curved surfaces and well balanced proportions of clear and shaded spaces.

v) Creative use of space:

Fifth, aside from the framework and parts of the stadium that will remain constant, the center of the stadium must be considered as it will be a focal point for performers, employees and the audience. This space must be impressive, creative and very much alive.

vi) Integrating stadium, city and landscape:

Sixth, an engineer should pay attention to the relationship between the stadium and its natural and urban surroundings. There may be particular aspects of the city that the stadium construction must conform to create coordination.

1.5 SYSTEMS TO COVER LARGE COLUMN FREE AREA

Different structural systems to cover large column free area are developed and employed in the world today. So basically they all systems came from the basic of "space structures". Following are the most common space structure systems for the large column free area structure. [3]

1) Single and double layer grid
2) Braced dome
3) Braced folded structures
4) Stressed skin Systems
5) Cable suspended roof structures
6) Tensile membrane structures
7) Tensegritic structures

1.5.1 Single and double layer grid:

Grid has certain common characteristics whether it is the single layer, double layer or multilayer grid. Grid carries loads by three dimensional actions. Loads applied at a point are not merely carried by the members meeting at that joint but are dispersed to be shared by a large number of other members. So grid has the ability to disperse heavy concentrated loads throughout the members of the grid. Grid may be defined as two or more sets of parallel beams intersecting each other at right or oblique angles and loaded by an external loading system composed of forces normal to the plane of the network and/or moments whose axes line lies in this plane. This loading produces bending and torsion in all the members. The main characteristic of grid construction is the omni directional spreading of the load as opposed to the linear transfer of the load in an ordinary framing system. Grid behavior differs from dome behavior in that the load is carried by bending rather than by a primarily membrane like action. Thus the most important type of rigidity in a single layer grid is the bending rigidity. [2]

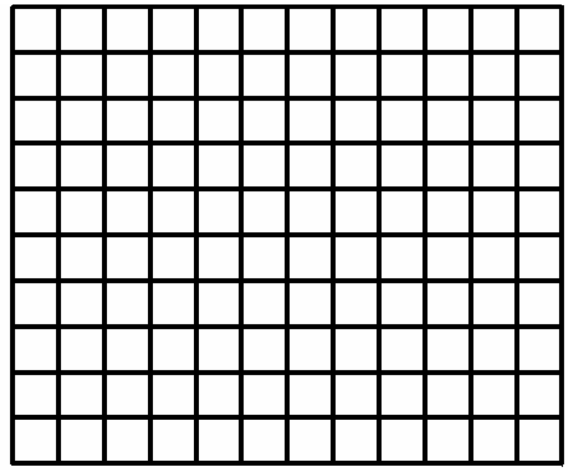


Figure 1.2 Single layer grid

Figure 1.3 Double layer grid

1.5.2 Braced dome:

Braced dome is a typical example of three-dimensional structure. It encloses a maximum amount of space with minimum surface and can be very economical in terms of material. A dome is curved in two directions, so it is one of the most efficient shapes for covering very large areas. Braced domes consist of single layer, double layer etc. single layer has the following principal types: ribbed domes, Schwedler domes, stiff jointed framed domes, plate type domes, network domes, Zimmermann domes, lamella domes, geodesic domes and grid domes. [3]

Figure 1.4 Braced dome structure

1.5.3 Braced folded structures:

Braced folded structures are very popular because of the two reasons. First is the appearance and second is the adaptability in a variety of shapes because of the wide variety of the folded systems. Steel frame folded plates have the advantage of simplicity in erection as well as good drainage because of good slope. Basically it is entire system making of trusses. [7]

Figure 1.5 Braced folded structure- Braced barrel vault

1.5.4 Stressed skin systems:

Stressed skin structures are defined as the structures in which the cladding is designed as a load bearing member. The folded plate system is an example of stressed skin structure. In folded plate structure external loading is resolved into components acting in the planes of plates forming the structure. The skin forces can be resisted very well because they act in the direction of the greatest stiffness of the plates. [3]

1.5.5 Cable suspended roof structures:

Cable suspended roof structures may be defined as structures whose principal supporting elements are tension members draped between anchorages. From literature survey, it has been found that, cable structures are able to cover more area compared to any other large span structural system. Cable structures have evolved into their present form over the last few thousand years, and today represent the frontiers of Civil Engineering. As the modern day demands put forward greater and greater challenges for the construction of longer spans or taller structures, cable systems offer increasingly better solutions. Some important aspects of cable systems are good appearance and economy. Too many types of cable structure with suspension systems present opportunities for good appearance. Suspended roof structures which make use of steel cables are economical for even very large spans. Suspended roof structures not only used for stadium purpose but also been used for many industrial buildings, airport hangers, many public buildings, such as swimming pools, exhibition halls, etc. for which they have proved to be much cheaper than conventional roof structures. It has also been found that these structures provide good acoustics and ventilation. They have got a higher factor of safety against fire than conventional roof trusses which fail through the buckling of compression members when the heat rises above a certain temperature. The differential settlements of the supporting columns are resisted by the ropes efficiently. [4]

Figure 1.6 Cable suspended roof structure

1.5.6 Tensile membrane structures:

Membrane structures are defined as the structures in which the main load carrying members transmit applied loads to the foundation or other supporting structures by direct tensile stress without flexure or compression. Shear and flexural rigidities as well as buckling resistance are negligible. The main advantages are their curved surfaces, easy to ship and erect, less erection time, require no scaffold. [17]

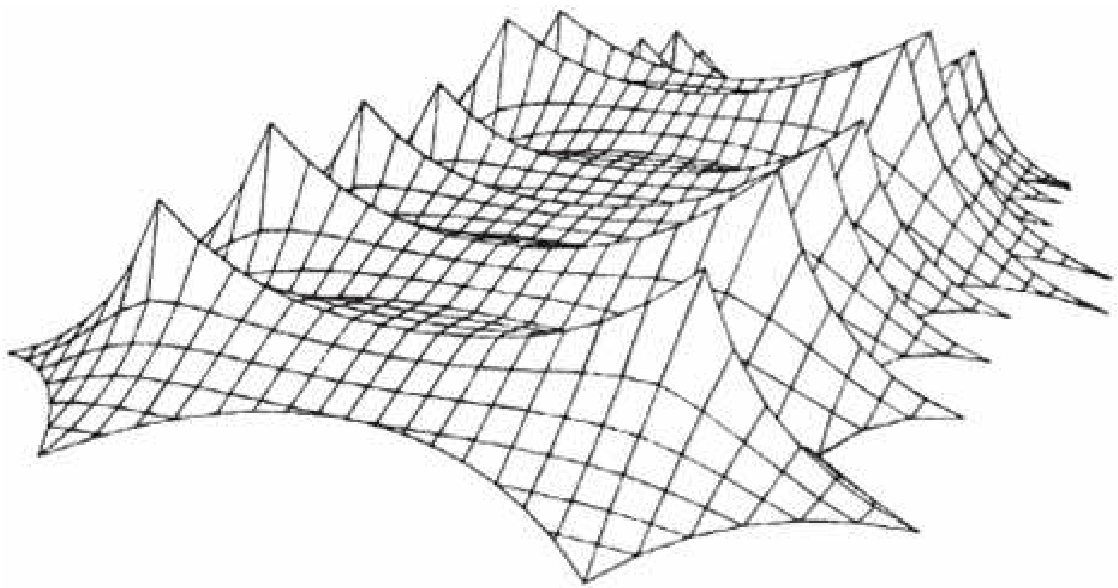


Figure 1.7 Tensile membrane structures

1.5.7 Tensegritic structures:

Tensegritic structures can be defined as a system which is established when a set of discontinuous compression components interact with a set of continuous tensile components to create a stable volume of space. It consists of bars and cable net. The bars may be arranged in such a way that no bar is connected to another. Tensegritic shells may be constructed by prestressing the bars against the cable net. Tensegritic structures are constructed from simple modules. [3]

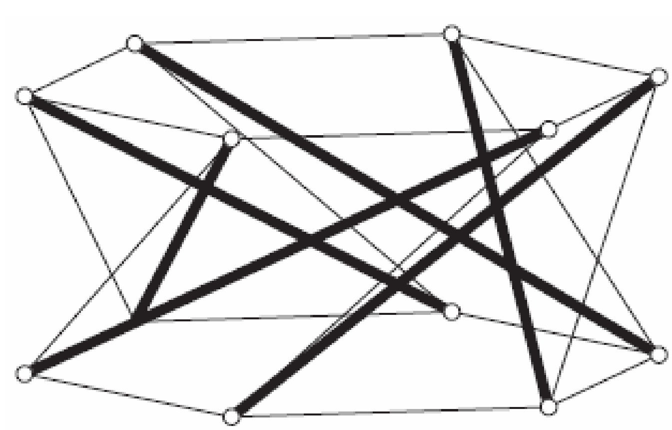


Figure 1.8 Tensegritic structure modules

Figure 1.9 Double layer tensegritic dome

Figure 1.10 Tensegritic arch

1.6 OBJECTIVES OF THE STUDY

- To study three space structural systems namely cable suspended roof (single and double layer), double layer grid (square on square offset-cornice edge) and Braced barrel vault (Lamella Type) to cover large span column free area of 40 m X 60 m.

- To calculate and compare approximate analytical results of cable suspension and double layer grid system with STAAD-PRO software.

- To find the proper modeling aspects for cable suspended roof structures to get exact results.

- To understand behavior of different space structure system like cable suspension system with single curved cable and double curved cable, double layer grid and braced barrel vault under different loading combinations.

- To study the effect of pretension in the cable during load application and all other parameters like convergence criteria, iteration process, change and SET NL command to perform cable analysis in double layer cable.

- Carry out exact analysis using STAAD-Pro for different space structural systems under static and dynamic load condition.

- Design and detailing of various components of indoor sports stadium for all three space structural system.

- To develop various types of connections like cable to strut (Tension member to compression member), cable to column (Hinge connection), cable to Ground (Gravity+ ground anchor), Mero Node connections, (for structural steel tubes in case of double layer grid), stub details, structural steel tube to concrete column, RHS to RHS connections, RHS to concrete column connections, seating gallery (slab-beam), column beam junctions etc.

- Carry out quantity analysis to find structural cost comparison between all three structural systems and find the structural cost per unit area to cover large span column free area of 40 m X 60m.

1.7 SCOPE OF THE PRESENT WORK

- **Literature survey**

  Survey of literature related to various space structural systems (Cable suspended roof, Double layer grid, Braced barrel vault), structural materials (Cables, structural steel tubes, RHS sections etc.), cladding systems (A.C. sheets, G.I. sheets, fabric etc.) and components for indoor sports stadium.

- **Study and modeling**

  Study and Modeling of different types of space structural systems with appropriate different combinations of structural materials:

  Viz: 1) Cable suspended roof (single and double layer)

  2) Double layer grid (square on square offset-cornice edge)

  3) Braced barrel vault (Lamella Type)

- **Detailing**

  Detailing of each component of stadium for each structural systems

- **Comparative study**

  Carrying out structural cost comparison study of indoor sports stadium when it is analyzed and designed with different types of space structural systems

- **Report**

  Report contains general introduction, analysis, design, detailing and structural cost comparisons of various space structural systems namely cable suspended roof structures (single and double layer), double layer grid and braced barrel vault to cover large span column free area of 40 m X 60 m.

1.8 ORGANIZATION OF THE MAJOR PROJECT-1

The report on **"Analysis and design of indoor sports stadium"** has been divided in to eight chapters as follows.

Chapter 1 provides introductory part of the report. Basic information like concept and historical development is discussed for indoor sport stadium and different structural systems like cable suspended roof structure, double layer grid and braced barrel vault. Requirement of long span structures and general discussion of stadium principles is discussed. Various space structural systems considering their various structural aspects to cover large column free area are mentioned. The chapter also emphasizes on the objective of study and scope of present work.

Chapter 2 deals with the literature review. In literature review, three types of space structural systems like cable suspended roof structure, double layer grid and braced barrel vault is discussed. Their basic structural behavior under loading, material used, their connecting devices, connection with ground, structural behavior under different types of support condition and supports structural behavior of various systems covered. The works related to analysis and design of structural systems to cover large column free area is discussed.

Chapter 3 covers the introduction to cable suspended roof structure, its various types, Basic of simply suspended cable structure and doubly curved cable structure its behavior under applied loading. Approximate analysis of Cable suspension structure with singly curved as well as doubly curved cable. Modeling aspects of cable in STAAD-PRO software is also mentioned.

Chapter 4 gives the analysis, design and detailing of cable structure including static and dynamic wind analysis and static seismic analysis for single and double curved cable structure when it is analyzed with anchor at 45^0. Design of all component of cable suspended roof structure is carried out. At last, detailing of various connections like cable to strut, cable to column, seating gallery connections, cable to ground connections, beam column junctions etc is to be carried out.

Chapter 5 presents the introduction to grid and braced barrel vault (space truss) systems, its various types, supporting methods, Basic of space truss structure and its structural behavior under applied loading. Approximate analysis of double layer grid using different theories is carried out and comparison of the results with exact analysis is carried out using STAAD-PRO software. Different types of connectors used in space truss are mentioned. Detailed theory for The MERO node connection is also described.

Chapter 6 gives the analysis, design and detailing of double layer grid (square on square offset- cornice type) and braced barrel vault (lamella type) systems (space truss). Analysis and design results are presented in tabular manner for both the systems. Detailing of various connections like structural steel tube to tube (Mero node connections), steel tubes to concrete column, stub detail, seating gallery (slab-beam), RHS to RHS, RHS to concrete column etc to be carried out.

Chapter 7 covers the quantity analysis of all three space structural systems i.e. cable suspended roof structure(double layer), double layer grid (square on square offset- cornice type) and braced barrel vault (lamella type) systems (space truss). For each system cost per unit area is calculated for an area of 40 m X 60 m.

Chapter 8 provides summary of the major project and scope of future work.

2. LITERATURE SURVEY

2.1 GENERAL

Analysis and design of structural systems used in indoor sports stadium is discussed by many authors. From the analytical as well as experimental work they find out some important conclusions. This chapter is a compilation of work done on cable suspended roof structure, double layer grid and braced barrel vault by different authors.

2.2 INDOOR SPORTS STADIUM

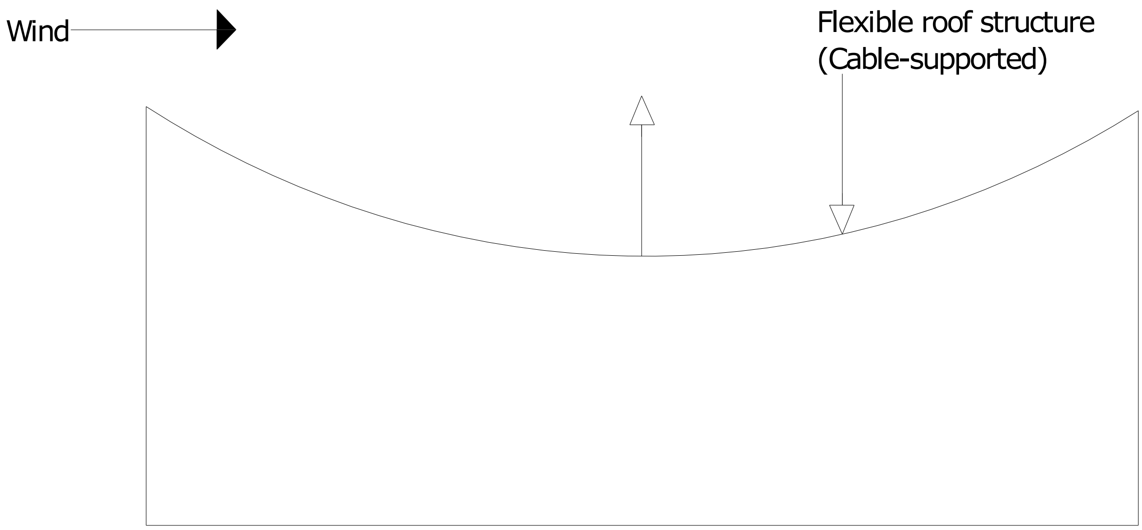
C P Nazir, (2003) [16] gives new type of stadium design with number of goals in mind such as accommodation of all major field games, creation of the best possible spectator experience and spectators line of sight in comparison with the best international facilities. Design procedure described in three parts. 1) Sight lines 2) superstructure 3) roof and proposed tier.

Richard Bradshaw, David Campbell, Mousa Gargari, Amir Mirmiran, and Patrick Tripeny (2002) [13] presents idea about special structures like sports arena i.e. made of space frames, cables, air-supported, tension membrane, folded plates and thin shells. Paper presents history, geometry, analysis, design, construction, applications and future of tension membrane structures. It also gives idea about space grid structures including history, different systems, different materials, analysis and design and future direction of space grid structures.

2.3 CABLE SUSPENDED ROOF STRUCTURE

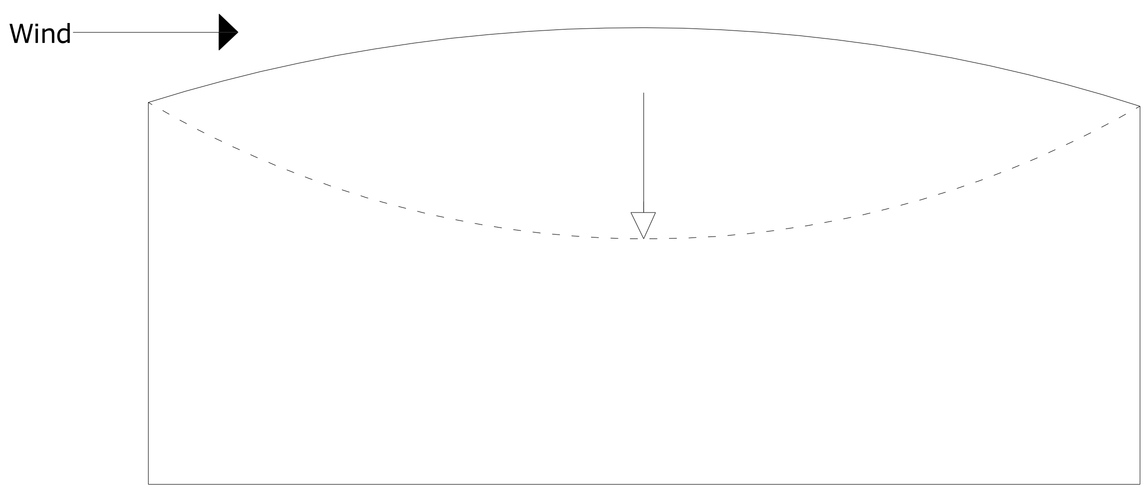
Many authors have suggested formulae for analysis of cable suspended roof structure, behavior of cable structure under different types of loading, natural frequency of the cable system, dynamic effects on structure and basic force systems for different types of supporting systems, different types of cable to ground connections.

Daniel L. Schodek (2002) [1] had given introduction about funicular structures; characteristics under different types of loading, general principals of funicular shapes, deformation shapes under different loading conditions are given. Analysis of Suspended cable structures under concentrated and uniformly distributed loads. Method for determining optimum cable sags. Dynamic effects of wind on flexible roof structure are described.



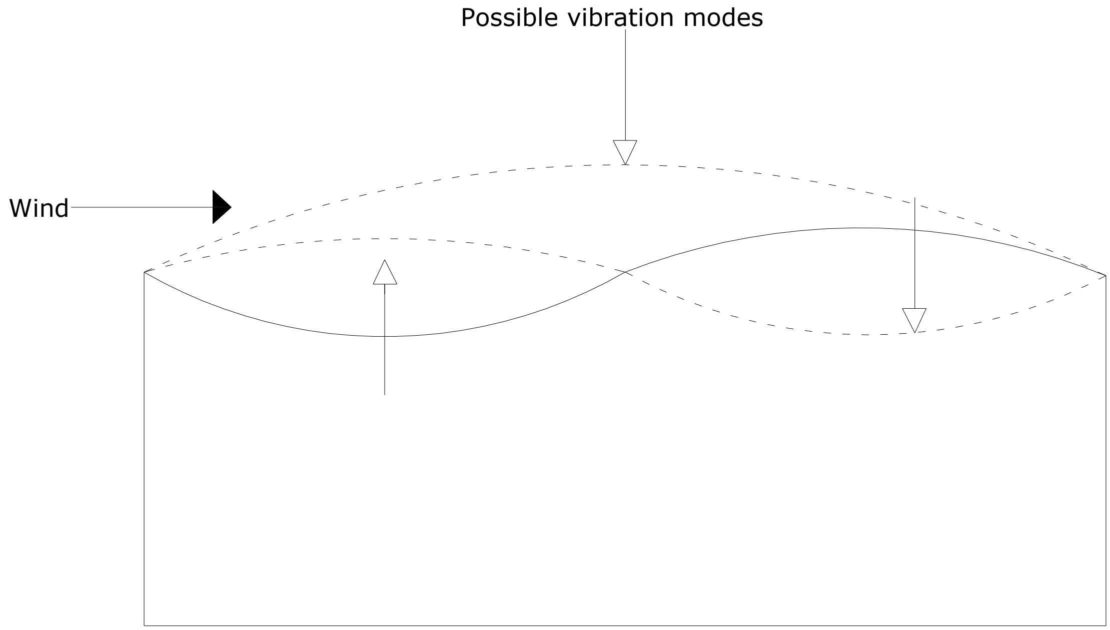
(a)

When winds blowing over roof surface in its naturally deflected shape cause suction forces to develop. These suction forces cause the flexible roof to begin rising as shown in Fig. 2.1 (a).



(b)

As the roof changes shape due to the suction forces, the effect of the wind on the new shape becomes one of the pressure rather than suction. This cause the roof to move downwards again as shown in Fig. 2.1 (b)

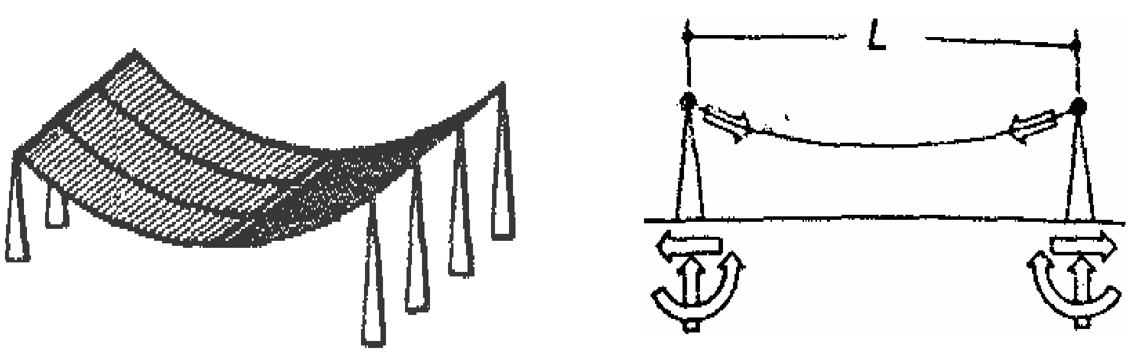


(c)

Figure 2.1 Dynamic effects of wind on flexible roof structure

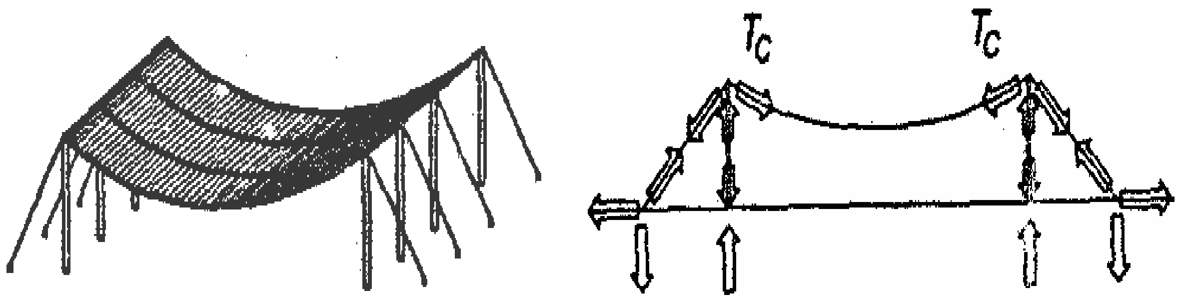
As the roof moves up and down, the effect of the wind alternately produces suctions and pressures causing further movements. A constant fluttering of the roof has been occurred as shown in Fig. 2.1 (c).

Behavior of different types of cable-support systems is also mentioned. Pier supports system is relatively good for shorter span only. The foundation must prevent the piers from overturning as shown in Fig 2.2 (a).

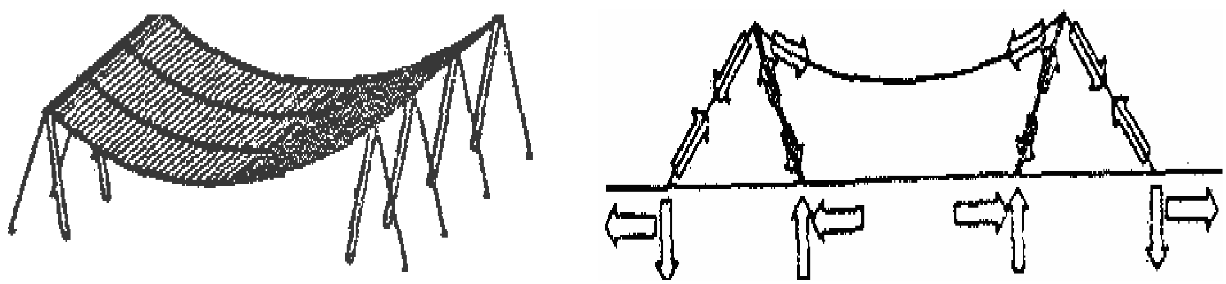


(a) Pier support

In case of guyed mast supports the mast carry only axial forces. The guyed cable foundations must prevent guy uplift and sliding as shown in Fig 2.2 (b).



(b) Guyed mast support



(c) Inclined guyed mast support

In case of inclined guyed mast, the masts carry only downward forces. This system is applicable for very long span Fig 2.2 (c).

Figure 2.2 Basic force systems for different types of cable supporting systems

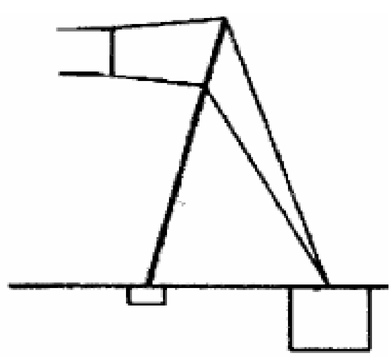
Dr N.Subramanian (1999) [3] discussed about space structures. A chapter on cable suspended roof structure contains introduction of cable structures, components of suspended roofs, main types of cable network systems i.e. cable supported and cable suspended. Different shapes of system, mainly circular, rectangular in which single layer systems, double layer systems. Some outstanding examples of cable suspended roofs, construction aspects of cable roofs including information about structural strand and Rope, cable fittings, placement and tensioning of cables is given. At last general consideration of design of cable roof is given. A complete design for a double layer cable suspended roof structure has also been included.

R. Vaidyanathan, P.Perumal (2004) [8] gives idea about cable components and their functions, different types of approximate analysis of cable structures, discussion on different types of arrangements for passing the cable on a supporting tower, effect of change in temperature in suspension cables. Various examples covered to show analysis of cable structure when it is supported at top using pulley and saddle.

S.Ramamurtham, R.Narayan (1998) [9] presents formulas and its derivations regarding vertical and horizontal reactions, Maximum & Minimum tension, total length of cable when any cable subjected to uniformly distributed load.

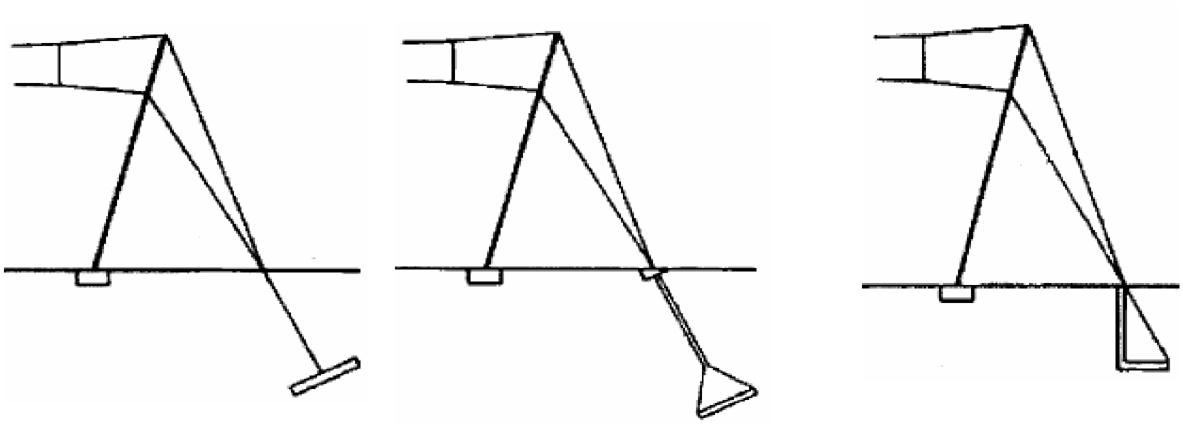
Frederick S. Merritt, Louis F. Geschwinder (1999) [10] present analysis of special structures like cable, arches, dome etc. general procedure for analyzing cable suspension system, derivation of different support reactions, forces acting at joints and displacements are given.

H. A. Buchholdt (1999) [4] discussed about different types of cable connections i.e. Cable-to-ground connection (tension anchors), Cable-to-frame connection, cable-to-cable connections etc. Tension anchors are used to hold cables when forces from the cables need to be transmitted directly to the ground. There are many types of tension anchors. The commonly used are gravity anchors, plate and mushroom anchors, ground anchors and tension piles. Gravity anchors work by using the dead weight of the anchor to balance the vertical component of the cable forces while the ground friction balances the horizontal components fig-2.3 (a). Gravity anchors are bulky. They are used in soil with poor force resisting properties such as gravel and sand or fine sand.



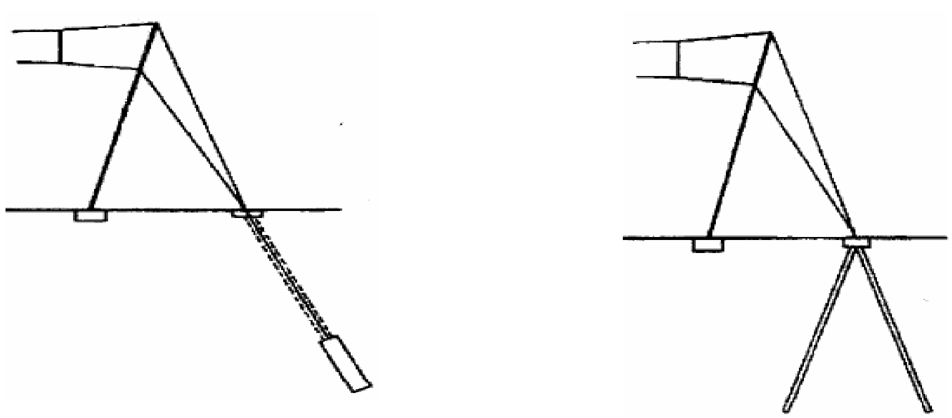
(a) Gravity

Plate, mushroom and Retaining wall footing rely primarily on the weight of the soil to resist the force from the cable. So compact soil condition is necessary to provide the necessary weight Fig 2.3. (b), (c) and (d).



(b) Plate (c) Mushroom (d) Retaining wall

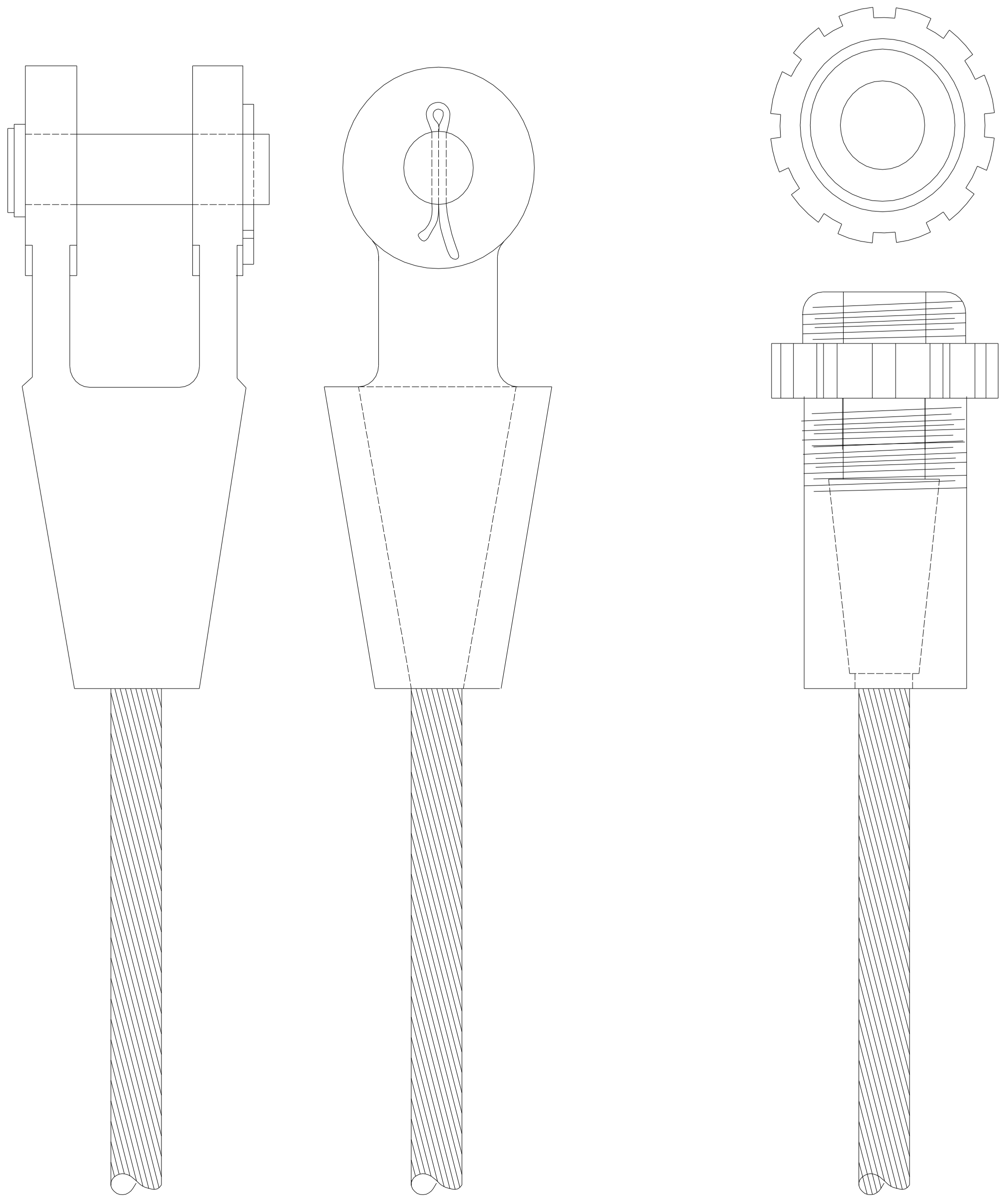
Ground anchors resist the upward pull from the cable through frictional forces between the anchor and the soil while the horizontal pull is resisted by the weight of the soil Fig. 2.3 (e). This anchor is thus suitable for use in soil which provide good amount of frictional resistance such as earth which contains much granular material or clay soil. Tension pile resists vertical force in the same way as ground anchors. However, the horizontal thrust in this system is resisted by the friction between soil and other tensile pile which is angled in the opposite direction to that of the cable Fig. 2.3(f).



(e) Ground Anchor (f) Tension Piles

Figure 2.3 Different types of cable to ground connections

Cable-to-frame connection forms the connection between a cable and a rigid structural frame, which could be either made of steel or concrete. Cable termination sockets are steel casting fitted near the end of a cable to hold the strands (Fig. 2.4). The external shape of sockets can be varied to suit individual design requirement, but for each shape variation, the basic dimensions of the socket cone or basket is approximately 5.5 to 6 times the cable diameter and the diameter of the cone approximately 2 to 3 times the cable diameter.



(a) (b)

Figure 2.4 (a) Socket terminal with pin connector

(b) Socket terminal with screw terminal

Fig. 2.5 and 2.6 shows a typical clamp connection between cable and steel frame and a concrete column respectively.

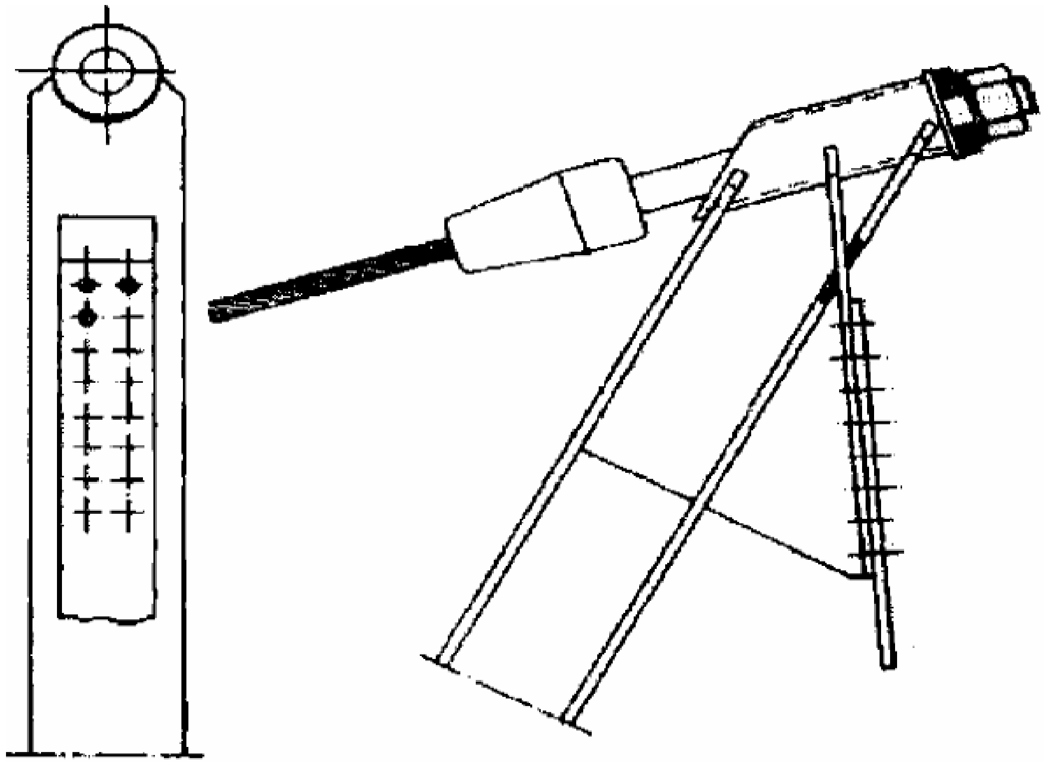


Figure 2.5 Attachment of cable with socket terminal to top of steel column

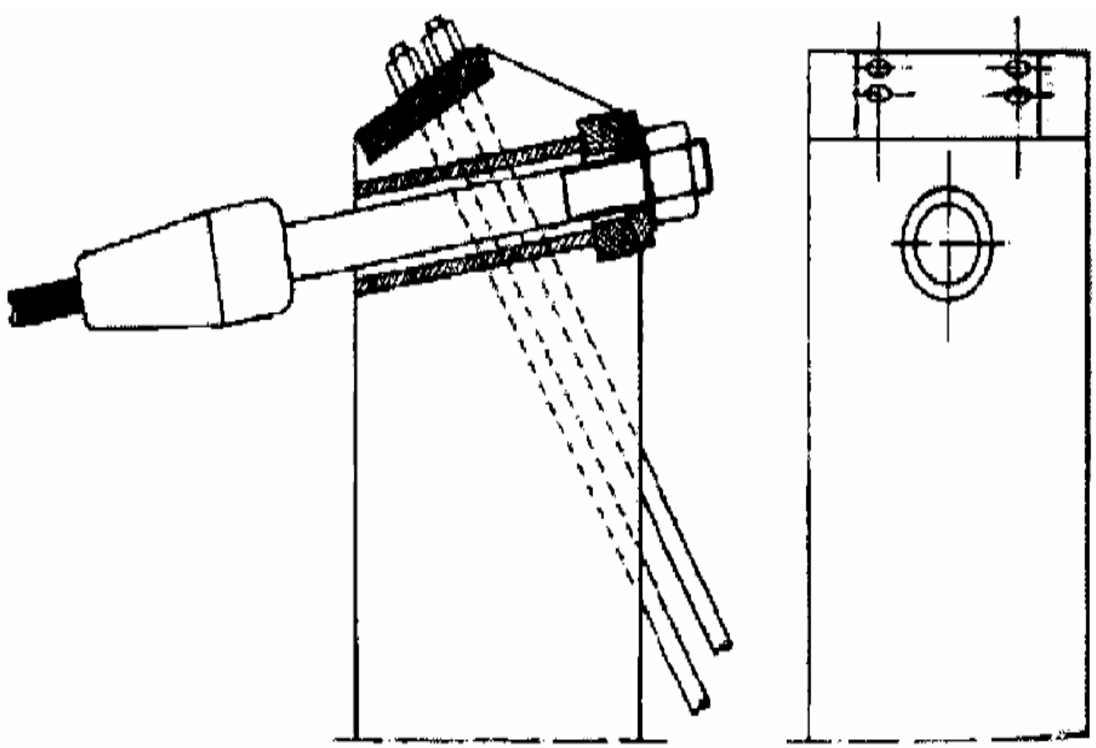
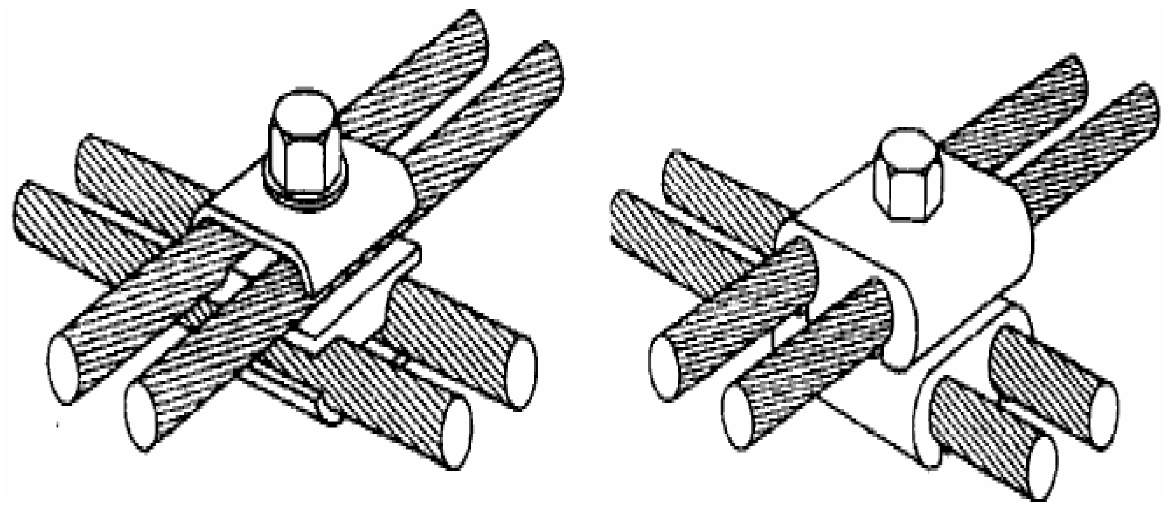


Figure 2.6 Attachment of cable with socket terminal to top of concrete column

Cable-to-cable connection is used to hold two cross cables so that they do not slide against each other. This connection simulates a pin joint which prevent relative vertical and horizontal displacement between two cables, but does not provide any rotational restrain.

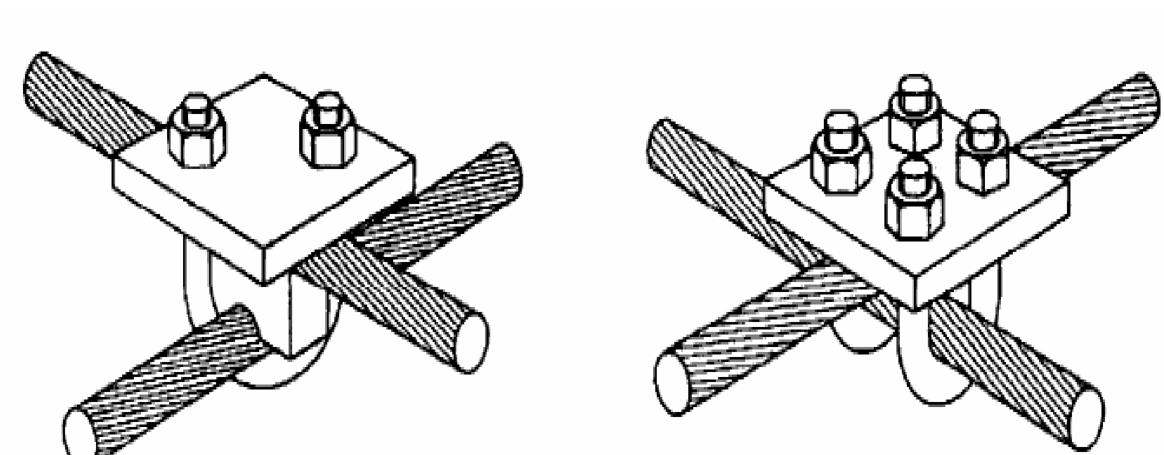


(a) (b)

Figure 2.7 (a) Fit on site cable clamp connection

(b) Prefabricated and factory installed cable clamp connection

For nets in which only two cables intersect at each joint, clamps of the types shown in Fig. 2.7 and Fig. 2.8 can be used. Where the cables are attached to edge cables, special clamps are required. An example of such clamp is shown in Fig-2.9.



(a) (b)

Figure 2.8 (a) Single u-bolt connection for cable net

(b) Double u-bolt connection for cable net

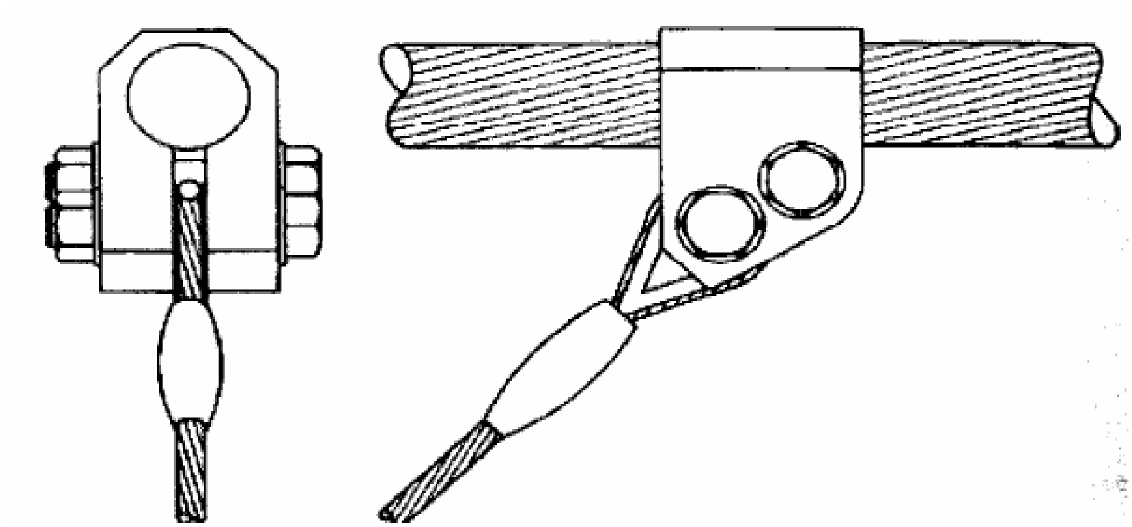


Figure 2.9 Detail showing clamp for connection of interior cable to edge cable

Dr C. Melbourne, P.Bullman (1995) [11] presents general introduction of load relieving roof system, its concept & different forms, and charts of deflection Vs Loads, Tension Vs loads and some parametric indicators are defined like initial stiffness ratio, deflection ration, load ration etc. are given.

Michael Barner, Michael Dickson (2000) [5] explains the philosophy of wide span lightweight structure, general philosophy of design of cable structure is given.

Peter broughton, Paul ndumbaro (1994) [6] gives general introduction of cable, analysis of general two-dimensional cable structure.

Dr. H J shah (2005) [12] explains the behavior of isolated footing under uniaxial bending. An example is given based on how to design an isolated footing when it is subjected to axial force and uniaxial moment.

Osamu Hosozawa, Kouhei Shimamura, Taro Mizutani, (1999) [14] presents use of cables as structural members in large span special structures. Cables gives good esthetics, light weight structure, expanded impression of space as well as well defined transmission of forces. An approach to handle thrust load by tie cables as well as tensioning of tie cable was explained. Another approach is using beam string structure to support the large 160m X 160m roof is given.

Minger Wu a, Mutsuro Sasakib (2006) [15] gives idea of basic behavior of a cable-stiffened system is investigated by numerical and experimental studies on a cable-stiffened column. To study cable-stiffened arch, Designed arch is investigated for (1) the pre-tension introducing process, (2) the loading behaviors and (3) the free vibration. Two models, i.e. model A for pulling cables and model B for elongating struts are used. The natural frequency and the damping ratio obtained through the free vibration experiment.

P.Krishna (2001) [17] describes the term tension structures. Different forms of tension, compression and flexure elements are discussed. Different roof supporting tension systems and tension roof structures also presented. Information about cable including cable systems also discussed. This paper also gives new trends in cable technology. It also gives idea about strands, stranded ropes, locked coil rope, spun cables, corrosion protection, cable end fittings, and fatigue of cable.

Horst Berger (1999) [18] addresses principal types of tensile structures, It includes point supported, A-frame supported, Arch supported and stadium domes.

2.4 DOUBLE LAYER GRID

G.S.Ramaswamy, M.Eekhout, G.R.Suresh (2002) [2] gives detailed information about space trusses. He deals with Introduction to space frames, Structural design of space frame components, preliminary design, and double layer flat space frames. He introduces with various types of connections systems used in space trusses now a days. Support design, connections between tube and anchor plate. A case study of a cylindrical braced barrel vault for roofing platform shelters at the Thirumailai railway station, Chennai, India is presented.

Dr N.Subramanian (1999) [3] discussed a complete chapter on single and multi layer grids. He gives idea about single and double layer grids, principle types, advantages, disadvantages, connectors, their behavior under loading, grid edge profiles, different methods of supporting double layer grids, cladding details, water drainage systems and at last many case studies has been presented. In chapter of connectors' different types of connectors has been discussed. Detailed classifications of connectors, different types of systems i.e. ball joint system, Mero system, Nodus system, Catrus, KT-truss, socket joint etc. the complete design of node is shown at last to find the thickness of joint. Other patented systems like Space-SERC Jointing system developed by structural engineering research center at Chennai, India also mentioned. A chapter regarding approximate methods of space structure is presented. In case of double layer grid there are too many approximate methods have been discussed. A comparative analysis has been carried to find the percentage variation between all approximate methods and exact analysis carried out by computer and is presented in a tabular manner. A complete design regarding double layer grid structure (using Mansard grid edge profile) is also presented.

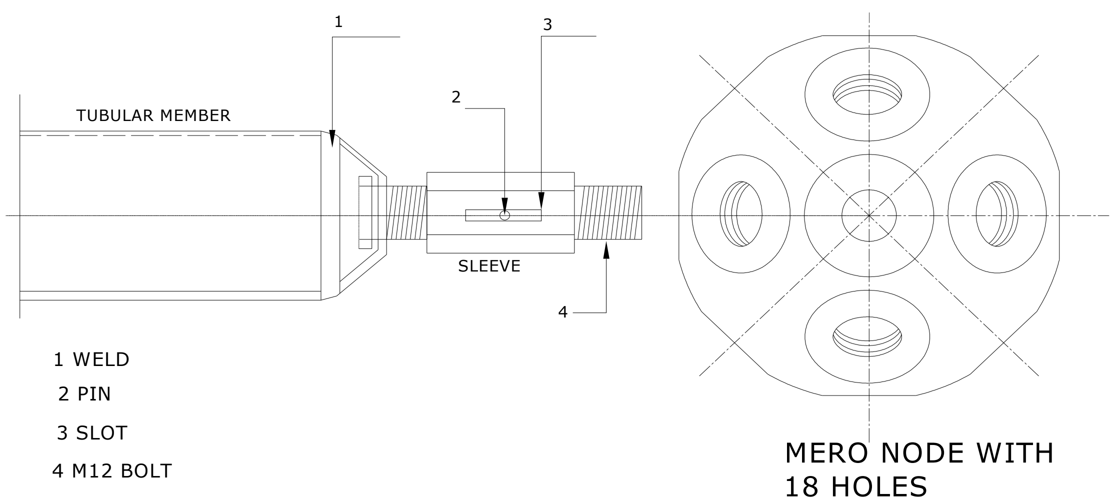


Figure 2.10 Typical Mero node and tubular member with its end fittings

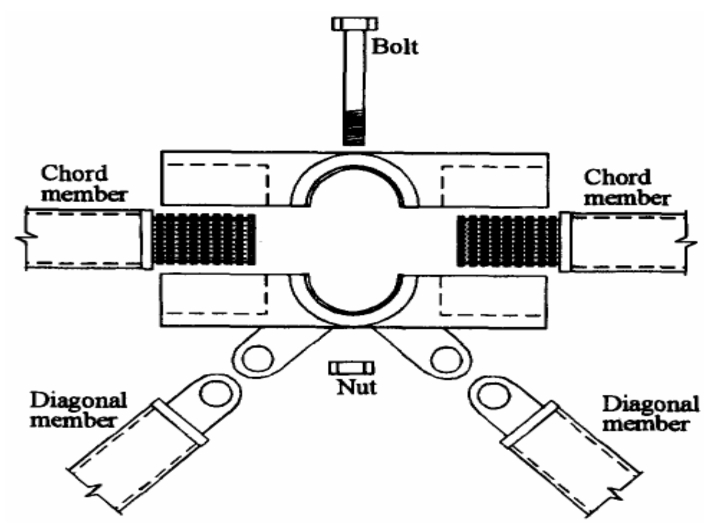
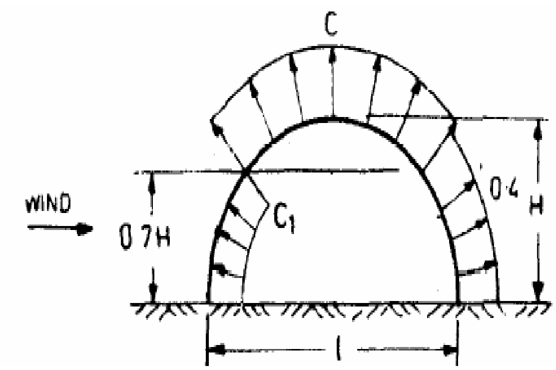


Figure 2.11 Typical Nodus node with member end fittings

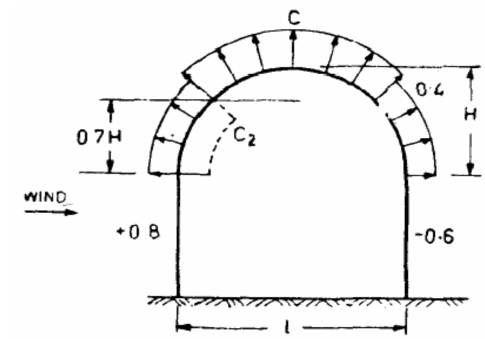
2.5 BRACED BARREL VAULT (SPACE TRUSS)

Z. S. Makowski (1985) [7] has discussed too many papers regarding Analysis, Design and construction of Braced barrel vaults. He discussed about history of development, recent achievements all over the world, Determination of wind loads, formex formulation of braced barrel vaults, and comparison of the structural behavior of various types of braced barrel vaults. A paper is also presented on the design and construction of the Liverpool international garden festival exhibition building.

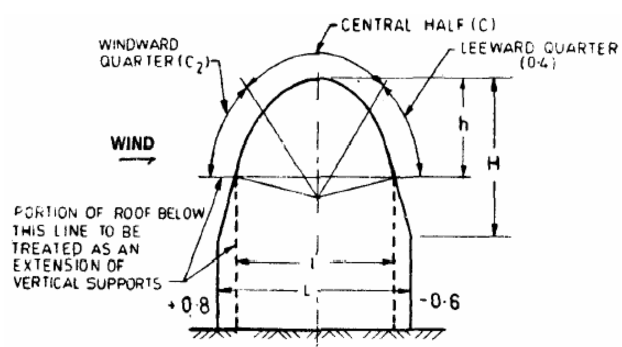
Dr N.Subramanian (1999) [3] discussed about behavior of braced barrel vault system, principle types, buckling behavior, practical considerations and comparison of different external pressure coefficients of wind for different codes like Indian standard (Fig 2.12), British standard and wind loading handbook. A complete analysis example of braced barrel vault is given in chapter of approximate methods of analysis.



(A) Roof springing from ground level



(B) Roof on elevated structure



(c) Double curved roof

H/l	C	C_1	C_2
0·1	−0·8	+0·1	−0·8
0·2	−0·9	+0·3	−0·7
0·3	−1·0	+0·4	−0·3
0·4	−1·1	+0·6	+0·4
0·5	−1·2	+0·7	+0·7

(D) values of C, C1 and C2

Figure 2.12 External pressure coefficients for curved roof as per IS: 875 (part-3)-1987

2.6 MODELING

STAAD-PRO (2005) [19] graphical environment gives idea about how to model cable (Fig. 2.13), initial tension provided in the cable (Fig. 2.14), its analysis (Fig. 2.15), different parameters require during analysis etc.

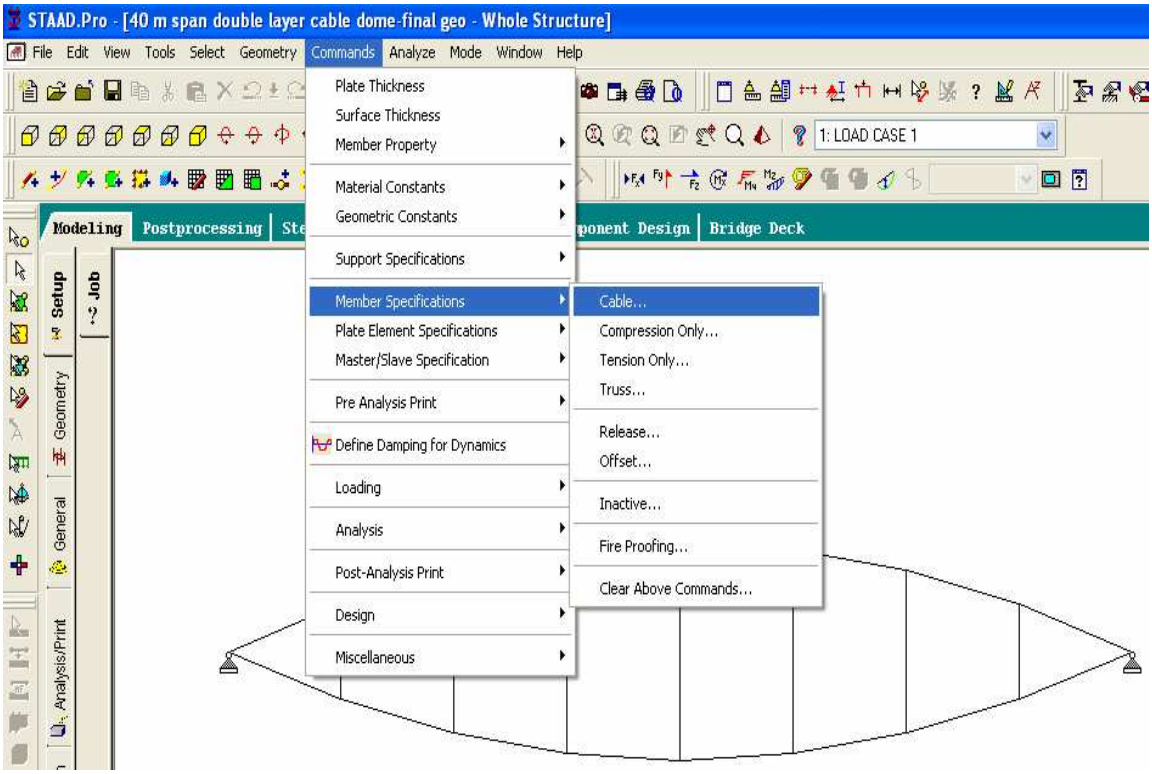


Figure 2.13 Initialization of cable

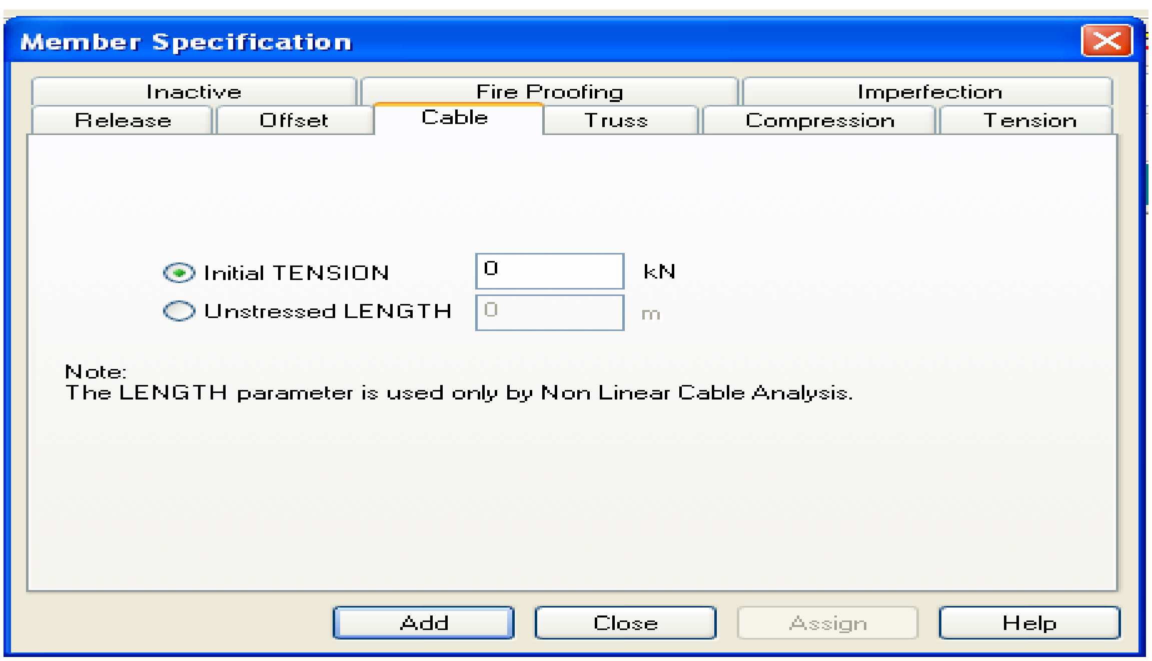


Figure 2.14 Application of initial tension

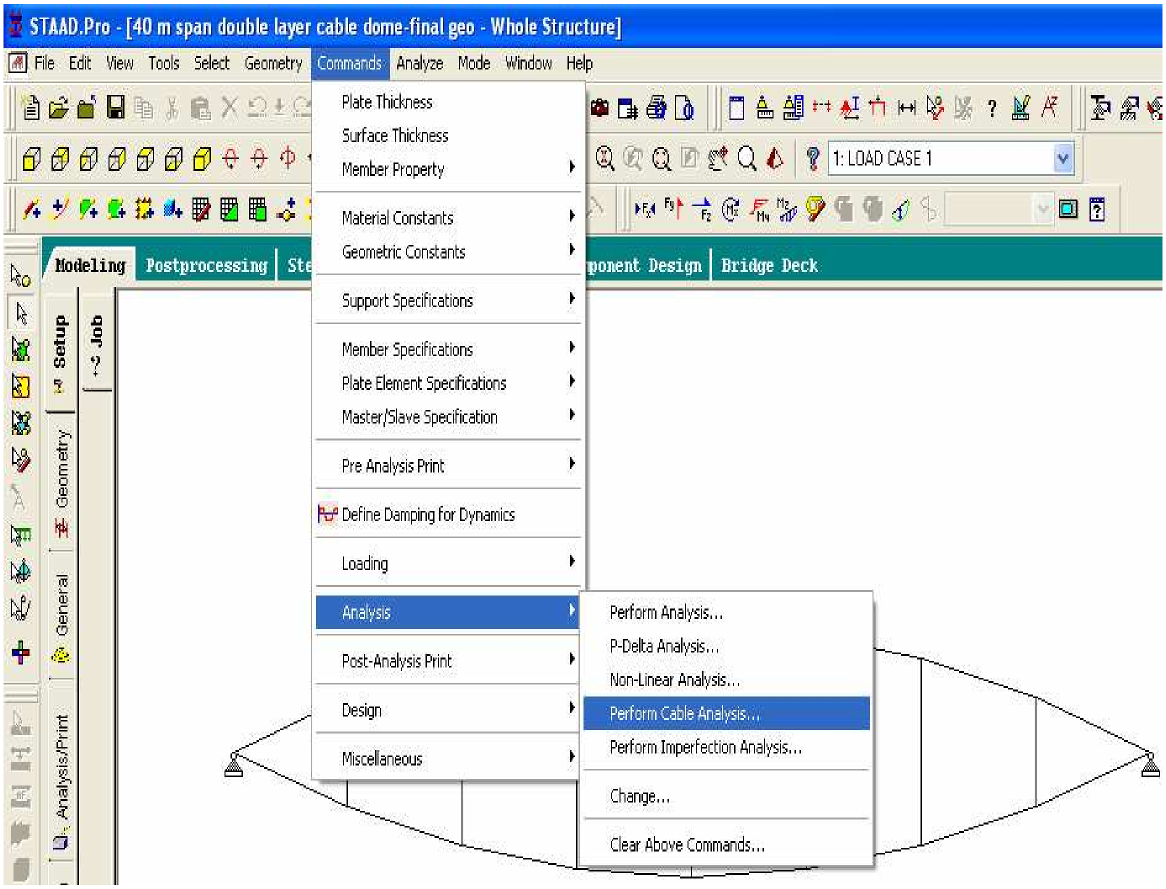


Figure 2.15 Performing cable analysis

During vary complicated geometry like BBV, user can draw figure in any drafting tool like Auto-CAD and import the same shown in Fig. 2.16.

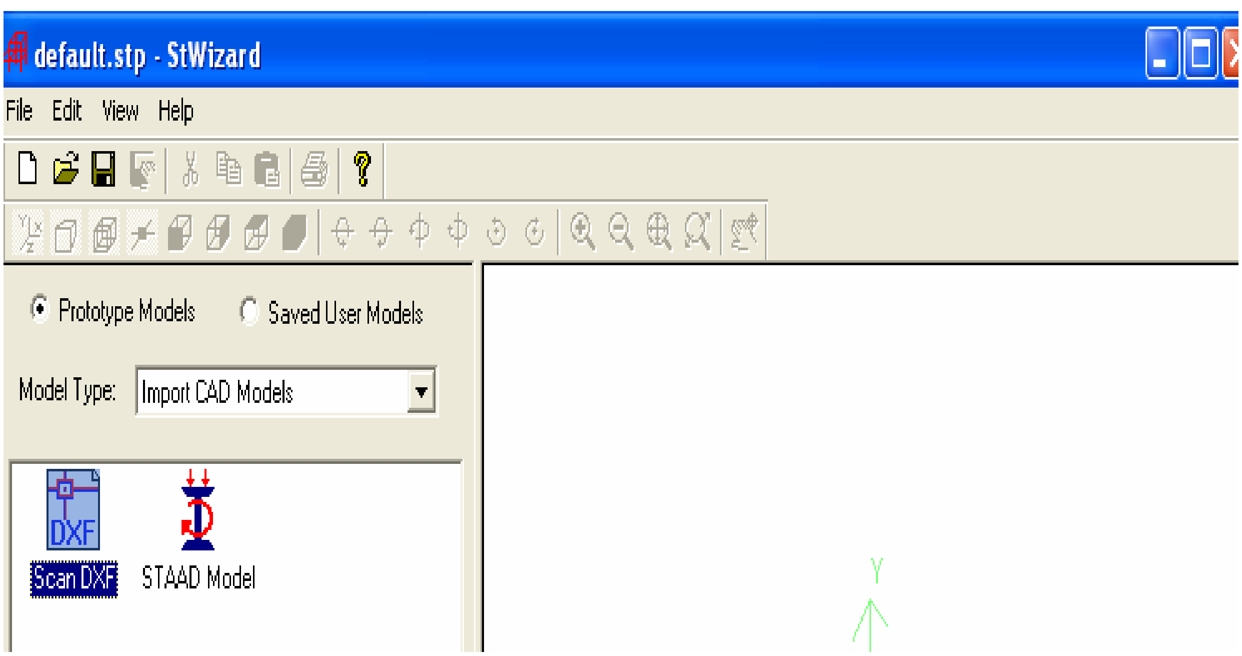


Figure 2.16 Import cad model in staad-pro

In case of section unavailability, STAAD-Pro also provide user to create user table shown in Fig. 2.17.

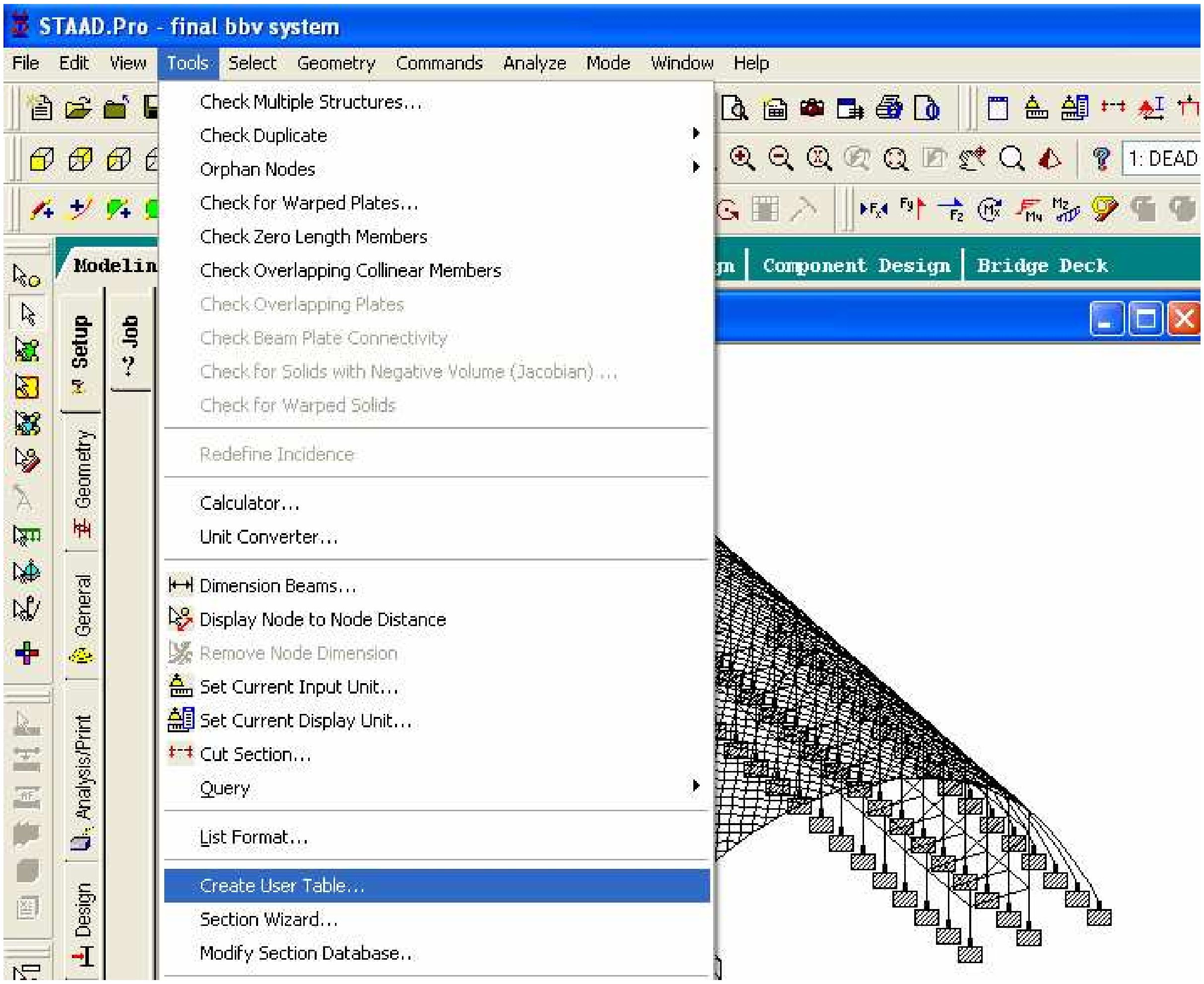


Figure 2.17 Use of user table

3. CABLE SUSPENDED ROOF STRUCTURES

3.1 GENERAL

Cable structures of different form are often covered under the general description of 'tension' structures. The term covers such structural elements or their combinations that bear loading primarily by developing tensile forces. These can be easily exemplified by membranes and cable assemblies of various descriptions. A freely suspended rope or a cable is a 'tension' element and since cable is a basic component in cable structures, the latter get covered under the broad definition of tension structures and are often described as such this is a wide selection available to architects and design engineers. [17]

Loads acting on the roofs are usually transferred to the ground either by direct stresses or by bending stresses or by a combination of both. It is well known that tension members make very efficient use of their material since their cross section is uniformly stressed. So, no stress reductions are required for buckling. Thus, tensile structures which utilize these tension members will result in optimal structures.

3.2 CLASSIFICATION OF CABLE NETWORK SYSTEM

Cable network system is mainly divided in two parts: (1) Cable supported roof system (2) Cable suspended roof system. [3]

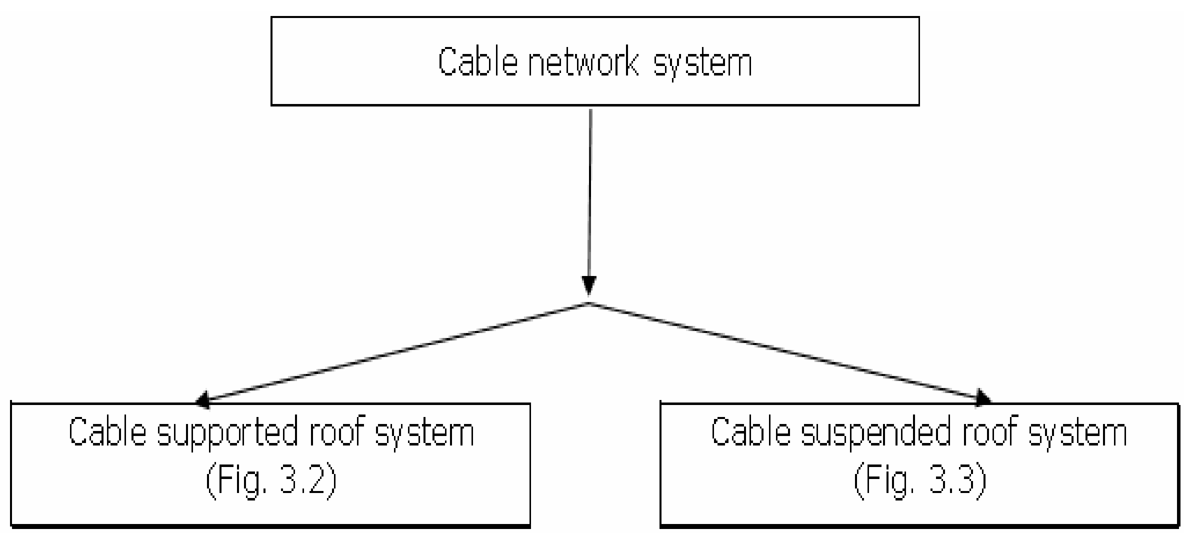


Figure 3.1- Classification of cable network

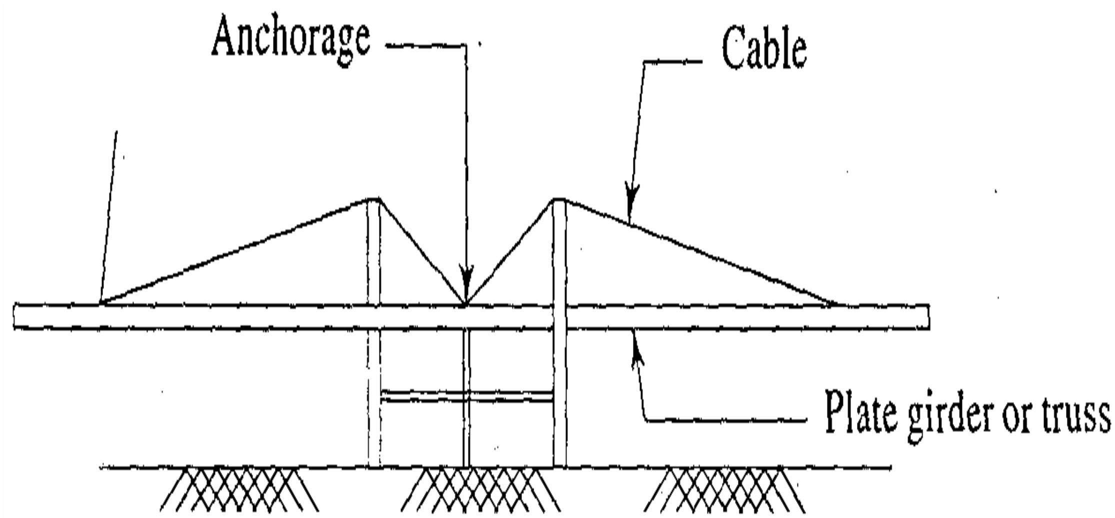


Figure 3.2- Cable supported roof system

Cable supported roofs are supported at one or more than one points by cables. It is very useful where long span cantilevers are needed. Ex: Hangers. As such this type of system is not applicable for indoor sports stadium because of the need of clear view during game.

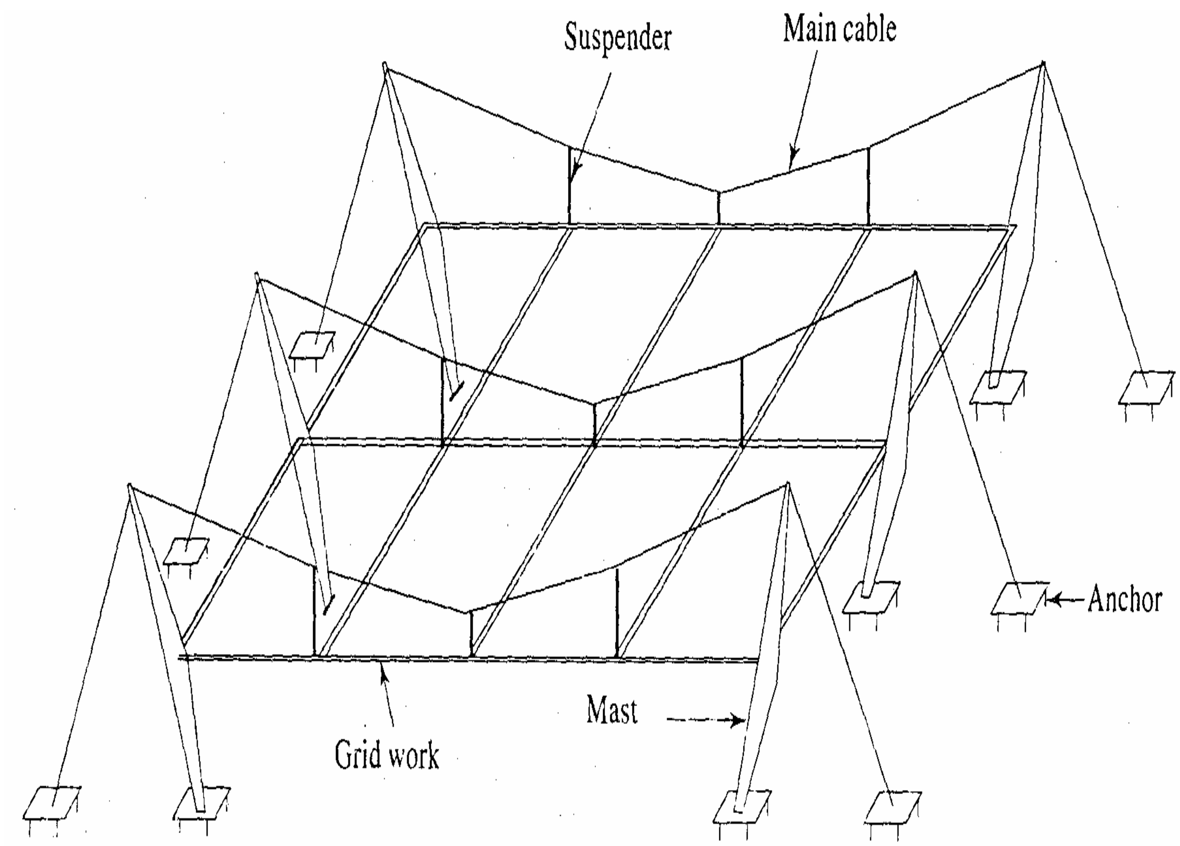


Figure 3.3- Cable suspended roof system

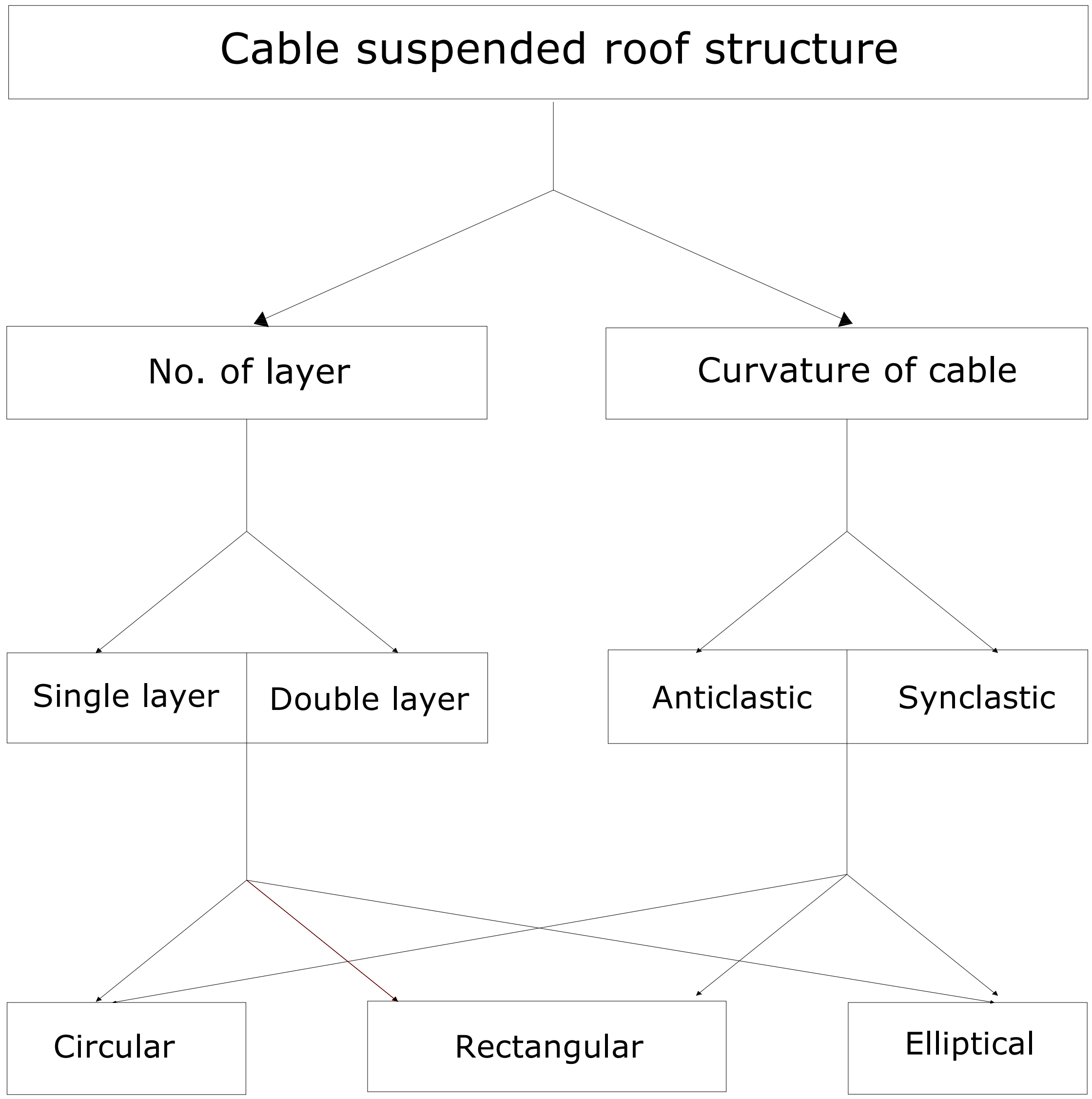


Figure 3.4- Classification of cable suspended structures

3.3 COMPONENTS OF SUSPENDED ROOFS

In suspended roof structures cable networks, vertical supports, anchorages and stabilizers are used to generate the roof structure. Vertical supports are needed to provide the required vertical clearances within the structure because cable sag below their supports. The cables are supported on posts or towers or on walls. Anchorages are required to resist the tension in the cables. Usually any one of the following is adopted to provide sufficient anchorage: heavy foundation, pile foundations, part of building, perimeter compression rings and interior tension rings. [1]

3.4 SIMPLY SUSPENDED CABLE STRUCTURES

3.4.1 General

Simply suspended cable structures known as the structure whose roofs are supported by a single layer of non-pretensioned cables. Architectural shape formed by this system look like conventional buildings, but with a slightly marked deflected roof. For roofs with rectangular plan, cables hanging in vertical planes may be arranged parallel to each other (Fig. 3.5). In roofs which are circular or elliptical in plan, the cables may be suspended radially and attached at the perimeter to a compression ring and at the center to a tension ring (Fig. 3.6). An important characteristic which differentiate the simply suspended cable system from the other cable systems is that the cables in this system are not pretensioned. However, since the cables are not prestressed, they do not offer any stiffness. This results in considerable deflections under loading. The lack of stiffness of the cables also results in much movements of structure under wind loading and so chances of fluttering effect. Stiffness of the system must thus be supplemented through the stiffness of the cladding material. Fabric is therefore often the material of choice for the roofing material in simply suspended cable roofs. [4]

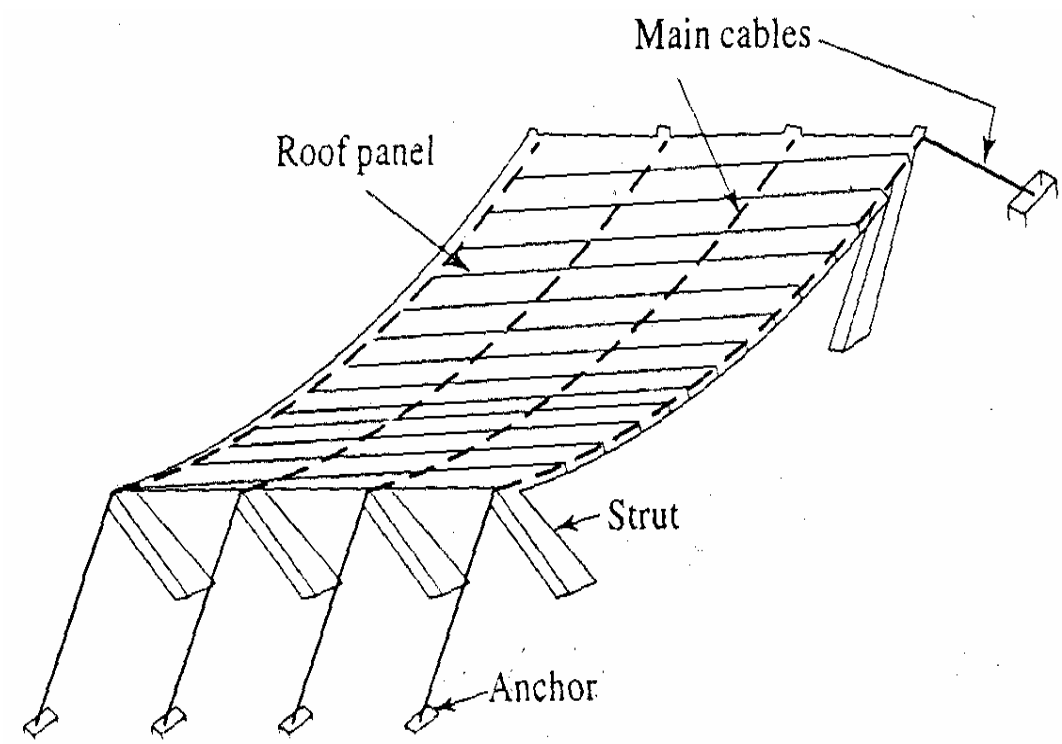


Figure-3.5 Singly curved single layer cable suspended roof

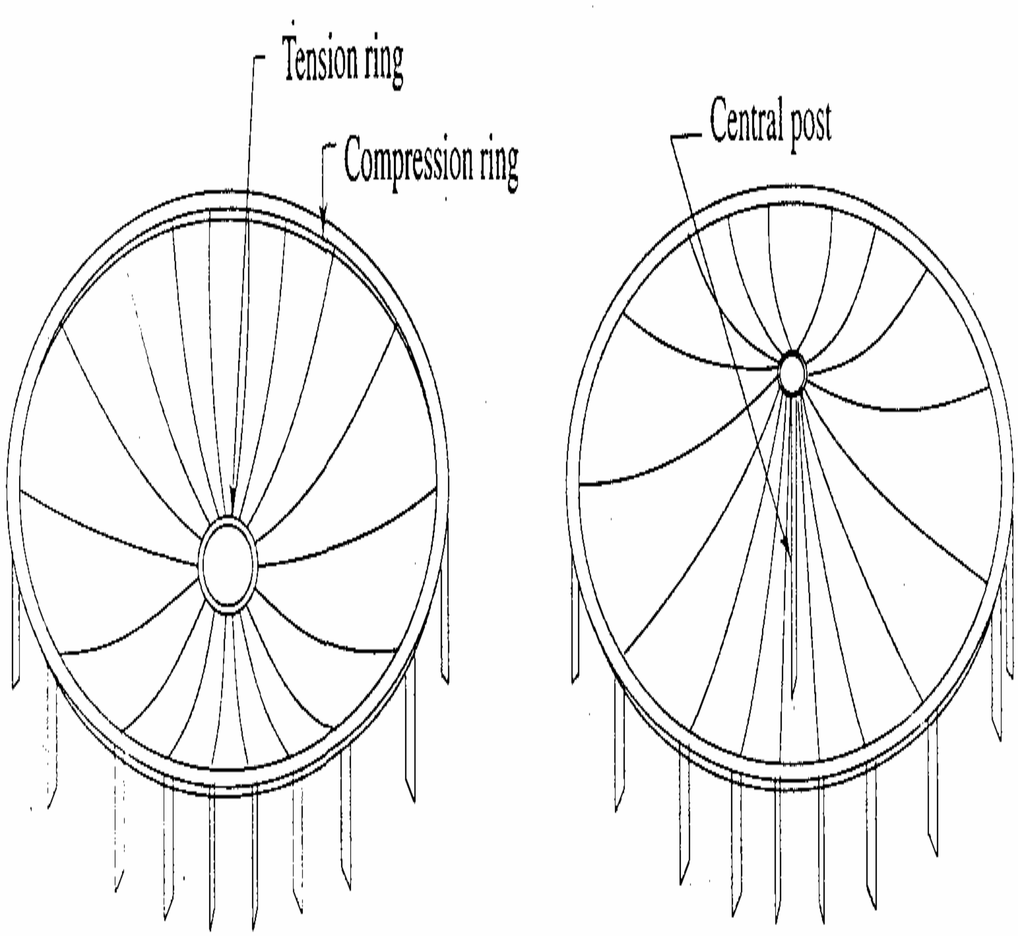


Figure-3.6 Doubly curved single layer cable suspended roof

3.4.2 Structural behavior

Since simply suspended cable structures behave very similarly to the beam column system. Only difference is that the "beam" supports loads through tension instead of bending. The cables work as beams on which the roof claddings are resting on. It is a simple load transferring mechanism where force acting on the roof is first carried by roof cladding, and then transferred to the cables. In a self balancing structure, that is one in which the structure supporting the cables has a geometry which permits the forces in the cables to be balanced internally, this force is passed on to a rigid frame before it continues on its way to the floor. In a non self-balancing building, where the geometry of the building supporting the roof is unable to resist the cable forces without the aid of ground anchor, the force is carried by the cables directly to the ground to which they are anchored. [4]

3.5 DOUBLE CURVED CABLE OR PRETENSIONED CABLE BEAMS

3.5.1 General

Double curved Cable is an improvement of the simply suspended cable system. It is formed by adding a second set of cables with reverse curvature, to the existing suspension cables.

The two-layer cable system fall into the following three principal categories:

1) circular in plan
2) rectangular in plan
3) Elliptical in plan

This second set of cables can be added in various manners forming three possible combinations- convex, concave and convex-concave (intermediate) beams, shown in Fig 3.7 to 3.12 respectively. This double cable arrangement works more efficiently as a load bearing system. Pre-tensioning of the cables also makes the structure stiffer as well as addition of strut or tie assembly respectively for convex and concave shape provides additional stiffing and change the natural frequency of both cables and so no chance of fluttering.

For systems which are rectangular in plan, a ring beam solution is not Practicable, and anchorages/ties must be provided to resist the horizontal peripheral forces.

The choice between the ring beam system and an anchored system is dictated by a number of interrelated factors including the planning of the building, the plan dimension of the site and the nature of ground. If the building is high or the ground is of poor soil, ring beams are adopted. As a ring beam would be loaded only with uniform radial forces, and would therefore be subjected to pure compression. The ring beam is normally supported by vertical columns at close spacing. Thus, bending moments and shear forces in the vertical plane are present in addition to axial forces in the horizontal plane. [3]

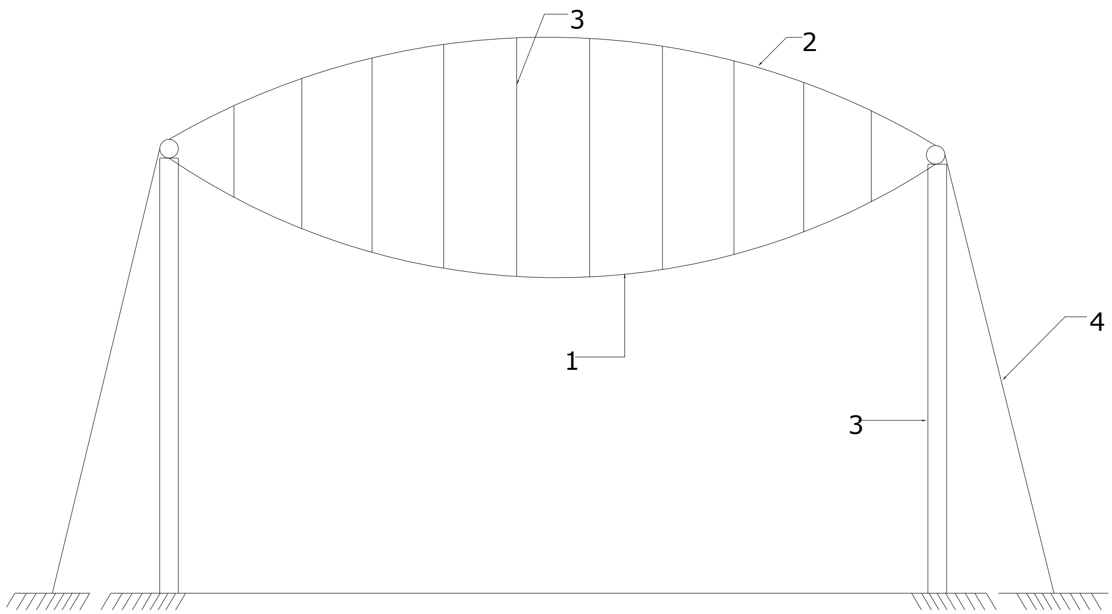


Figure-3.7 Double layer cable-convex shape for rectangular buildings

1- Bearing member (Main cable),

2- Stabilizing member (secondary cable),

3-Strut,

4-Tie/Anchorage

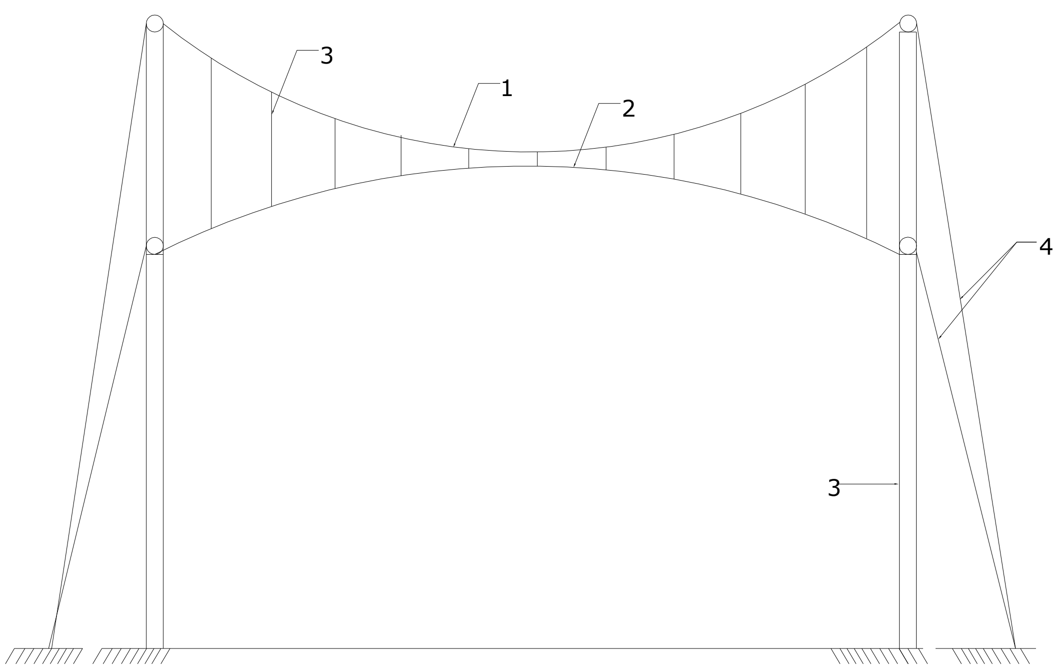


Figure-3.8 Double layer cable-concave shape for rectangular buildings

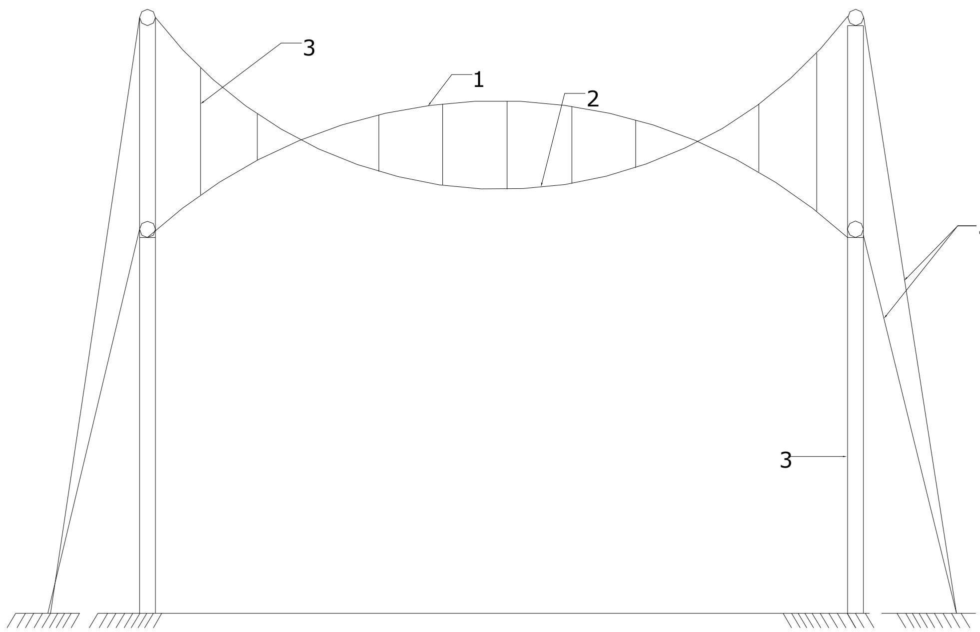


Figure-3.9 Double layer cable-concave-convex combination shape for rectangular buildings

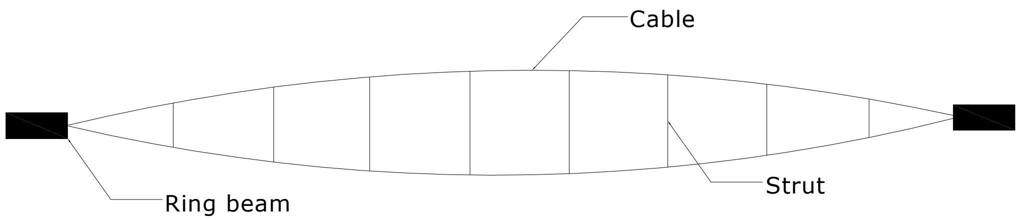


Figure-3.10 Double layer cable-convex shape for circular buildings

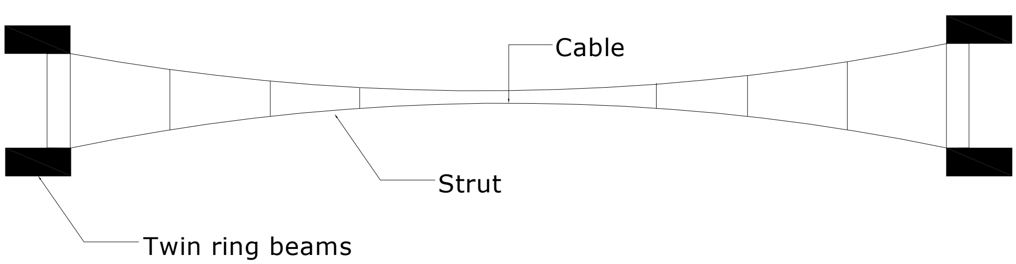


Figure-3.11 Double layer cable-concave shape for circular buildings

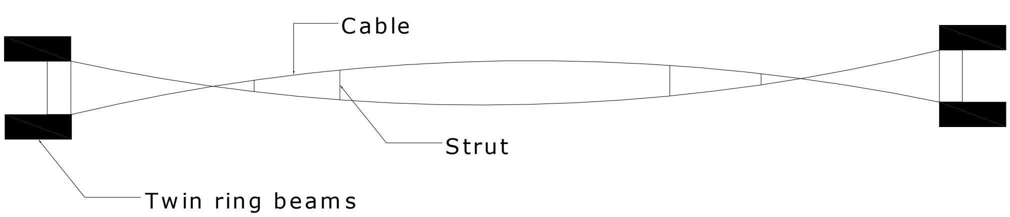
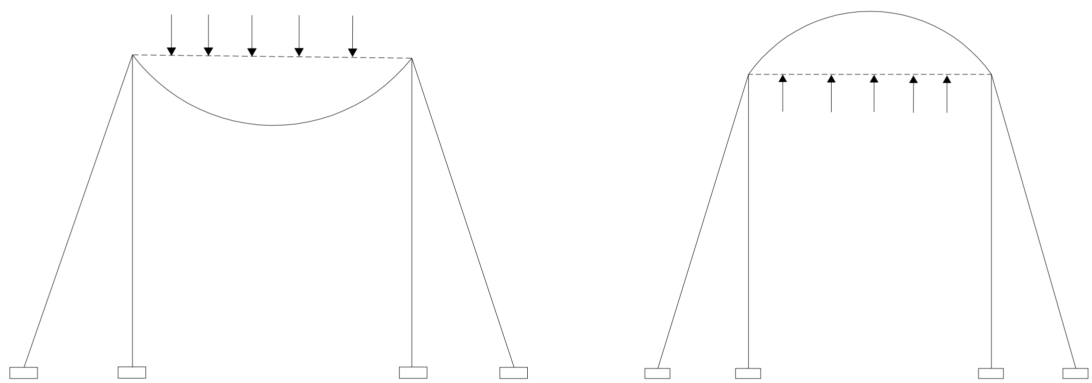


Figure-3.12 Double layer cable-intermediate shape for circular buildings

3.5.2 Structural behavior

As we know double curvature cable has two sets of cables having opposite curvature to each other. So when vertical load is applied on cables, it is able to carry vertical load in upward and downward direction with equal efficiency, The set of cable with convex curvature carries the downward force while that with concave curvature resists uplift. As shown in Figure 3.13(a) when a downward force acts on the structure, the pretensioned force in cable A is increased while the tension in cable B is reduced. When the structure is subjected to an upward force this force increases the tension in cable B and reduces the prestressing force in cable A. [5]



(a) Downward load (b) Uplift load

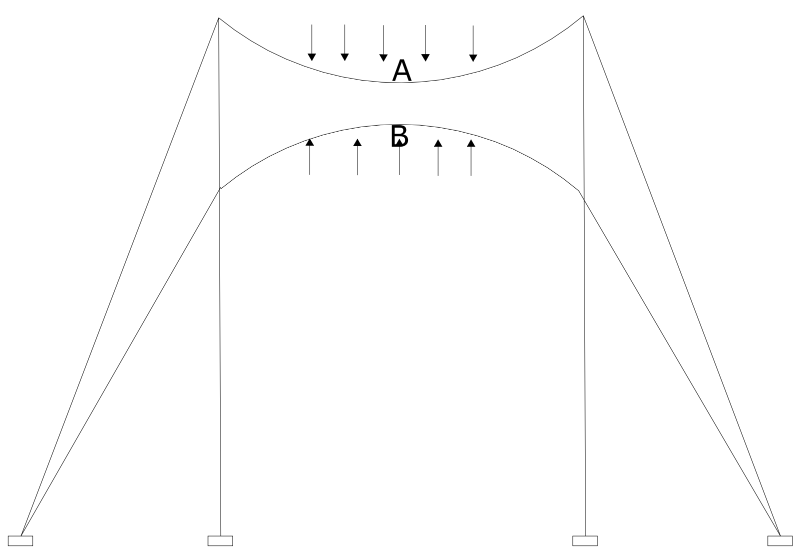


Figure-3.13 Structural behavior of a prestressed cable beam

3.6. SYNCLASTIC AND ANTICLASTIC CABLE

A Synclastic surface has the same kind of curvature in all directions while for anticlastic surface has opposite curvature in principal orthogonal direction i.e. concave in one direction and convex in other direction. [3]

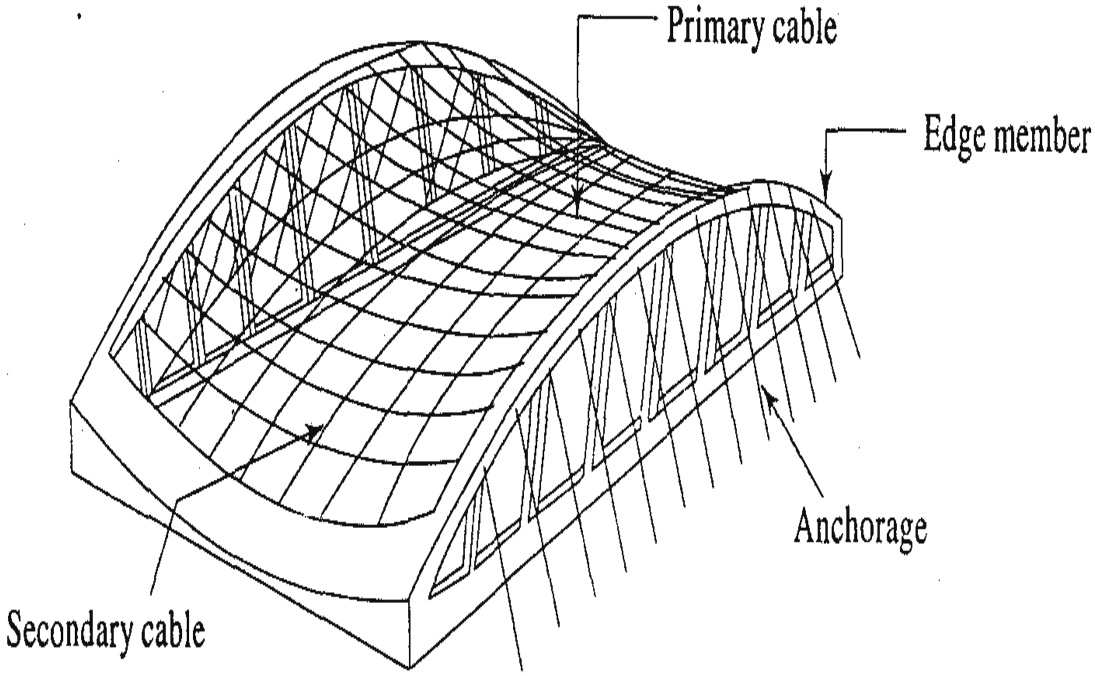


Figure-3.14 Anticlastic cable for rectangular buildings

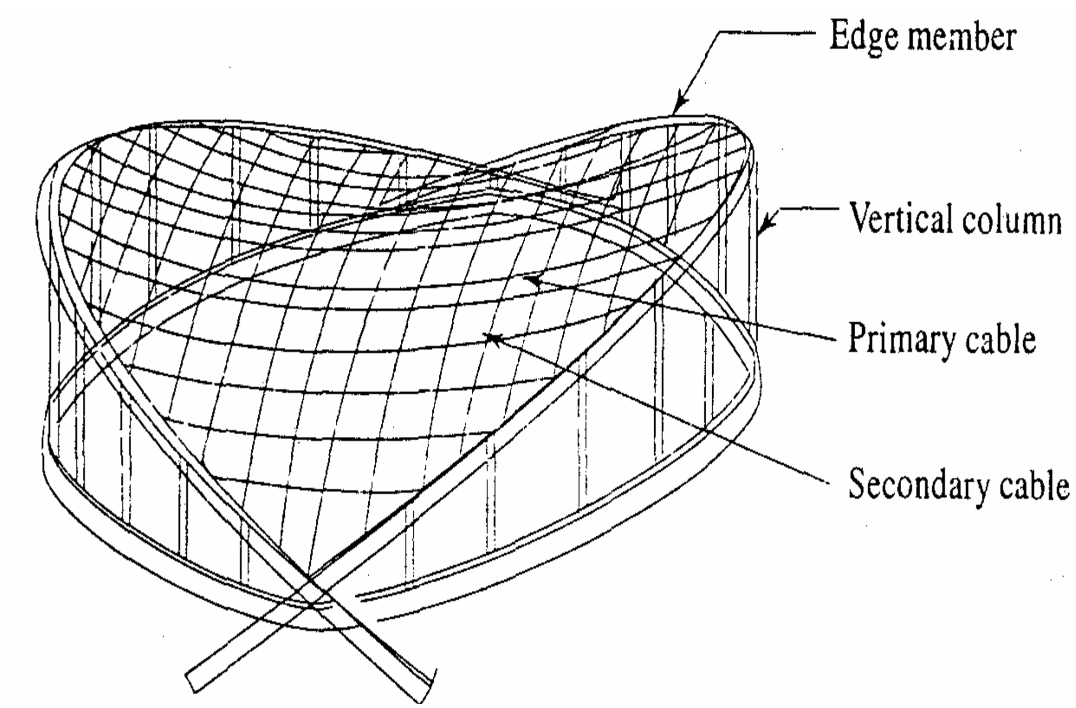
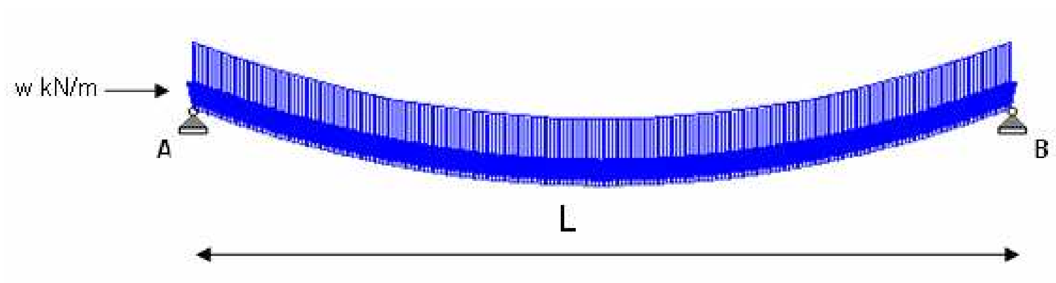


Figure-3.15 Anticlastic cable for circular buildings

3.7 APPROXIMATE ANALYSIS OF CABLE STRUCTURE

To get idea of accurate results, approximate analysis of structure is required. Basic theory of cable is derived from its catenary shape under loading. The all equations regarding horizontal and vertical reactions are the same as that of the simply supported beam subjected to uniformly distributed load. [9]

Some of the important equations are,



Vertical reactions,

$$Va = Vb = \frac{wL}{2} \qquad \text{. . . (3.1)}$$

Horizontal reactions or Minimum tension,

$$H = \frac{wL^2}{8h} \qquad \text{. . . (3.2)}$$

Maximum Tension,

$$T\max = \frac{wL}{2}\sqrt{1 + \frac{L^2}{16h^2}} \qquad \text{. . . (3.3)}$$

Length of cable,

$$L_1 = L + \frac{8}{3}\frac{h^2}{l} \qquad \text{. . . (3.4)}$$

Natural frequency of cable,

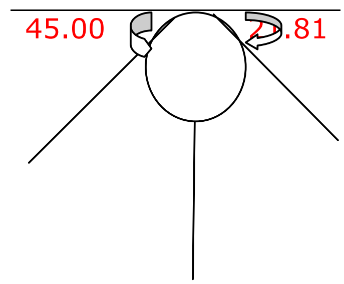
$$f_n = n\frac{\Pi}{L}\left(\frac{T}{m}\right)^{0.5} \qquad \text{. . . (3.5)}$$

APPROXIMATE ANALYIS OF SINGLE LAYER CABLE SUSPENDED STRUCTURE

CABLE SUBJECTED TO UDL-ANCHOR CABLES

DATA:

Load=	3.25	kN/m		
Span=	40	m		
Sag=	4	m		
stress=	120	N/mm^2	1.200E+05	kN/m^2
Density=	78	kN/m^3		
Inclination to horizontal=	45.00	degree		
Height of pier=	18	m		



Total length of cable=	41.07	m
Total load transmitted to the cable=	133.5	kN
The vertical reaction at each support=	66.73	kN
Minimum tension, H_{min}=	166.8	kN
Maximum tension, H_{max}=	179.7	kN
Inclination B of the suspension cable at the support with the horizontal is=	21.81	

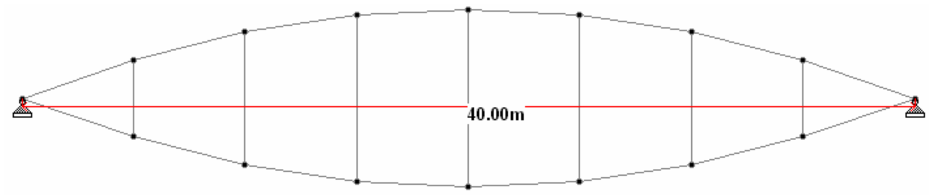
CASE 1 : CABLE IS PASSED OVER PULLEYS

Total vertical load transmitted to the pier =	194	kN
Net horizontal load transmitted to the pier=	39.7	kN
Max B.M. for pier =	715.07	kNm

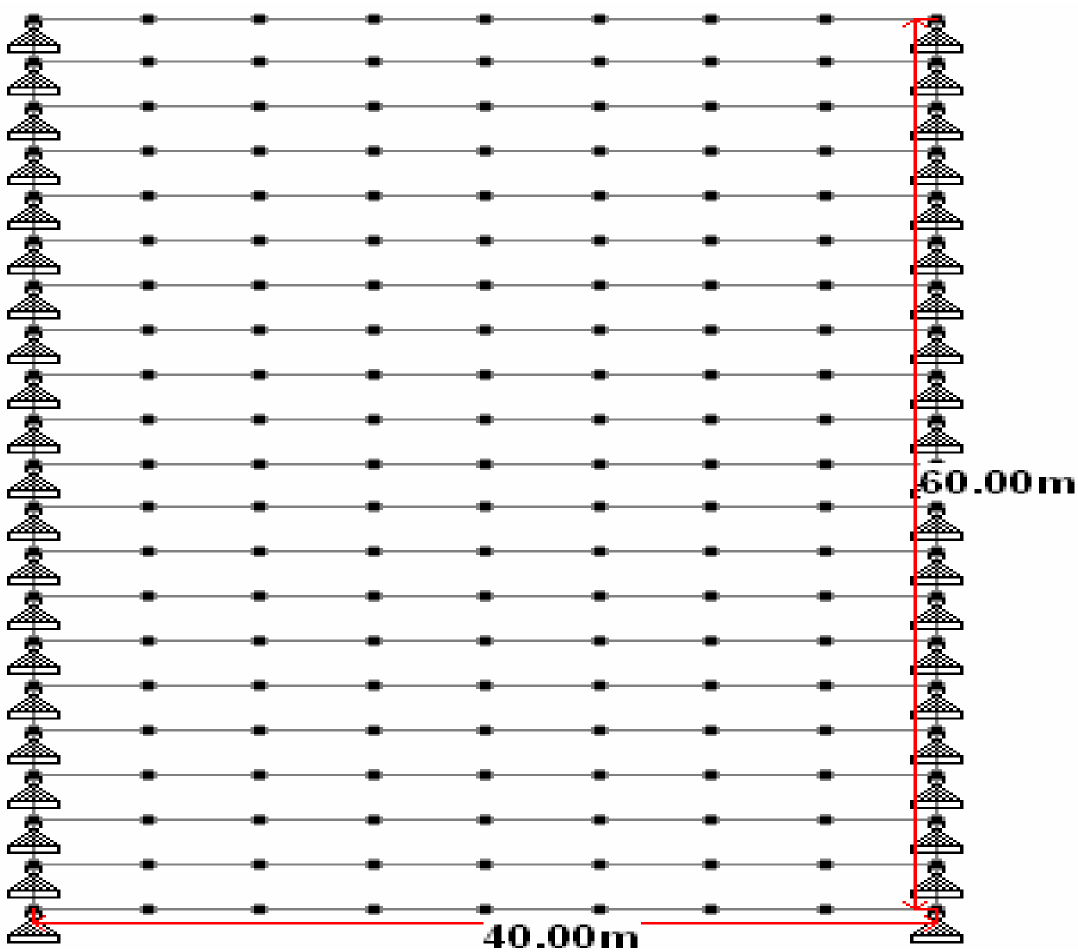
CASE 2 : CABLE IS PASSED OVER SMOOTH ROLLERS

Tension in the anchor cable=	235.8	kN
Total vertical load transmitted to the pier =	233.4	kN

APPROXIMATE ANALYSIS OF DOUBLE CABLE STRUCTURE



Elevation



Plan

<u>Data given:</u>

Location of project=	Rajkot	
width of structure, w=	40	m
length of structure, L=	60	m
Height of structure, H=	18	m
Roofing dead load=	1.0	kN/m^2
Live load considered=	0.75	kN/m^2

c/c spacing between columns=	3.0	m
Live load per meter run=	2.25	kN/m
Total load=	3.25	kN/m
Sag=	4.0	m

Since the weight of the top cable tends to depress the cable, we will put an arbitrary tension in the top,

To Produce an equivalent sag of 4 m

$$T = \frac{wL^2}{8h}\left[1+16(h/L)^2\right]^{0.5} \quad \ldots (3.6)$$

Taking half the roof load as w,

T= 87.51 kN

The bottom cable will carry the uniform load producing 4 m Sag of the upper cable plus the total roof load.

T= 262.5 kN

Check the natural frequency of the top and Bottom cable:

Cable Length:

L= 41.07 m

With dead and live loading contact with the top cable using 4 m as the contribution span for these loads, the mass is

m= W/g 0.323 kNs^2/m

$f_n = n*(л/L)*(T/m)^{0.5}$ 1.259 n

For the bottom cable, only the bottom cable weight will be used, since only the struts make continuity with top cable:

f_n= 4.991 n

Since the natural frequencies fn of the two cables are considerably different, no resonance is likely to occur. When one cable is at resonance, the other is at a different frequency, which acts to dampen the resonance vibrations so that the total vibration amplitude is kept small.

3.8 MODELING ASPECTS OF CABLE SUSPENDED STRUCTURE

To get accurate results of the cable structure it is necessary to form a proper model which represents good analysis. STAAD-PRO is used for modeling and analysis of cable structure. As in case of singly cable suspended roof structure there is no initial pretension is required. So member is defined as a beam and carry out analysis. While in case of double layer cable member is defined as a cable and provide initial tension as per calculation. [19]

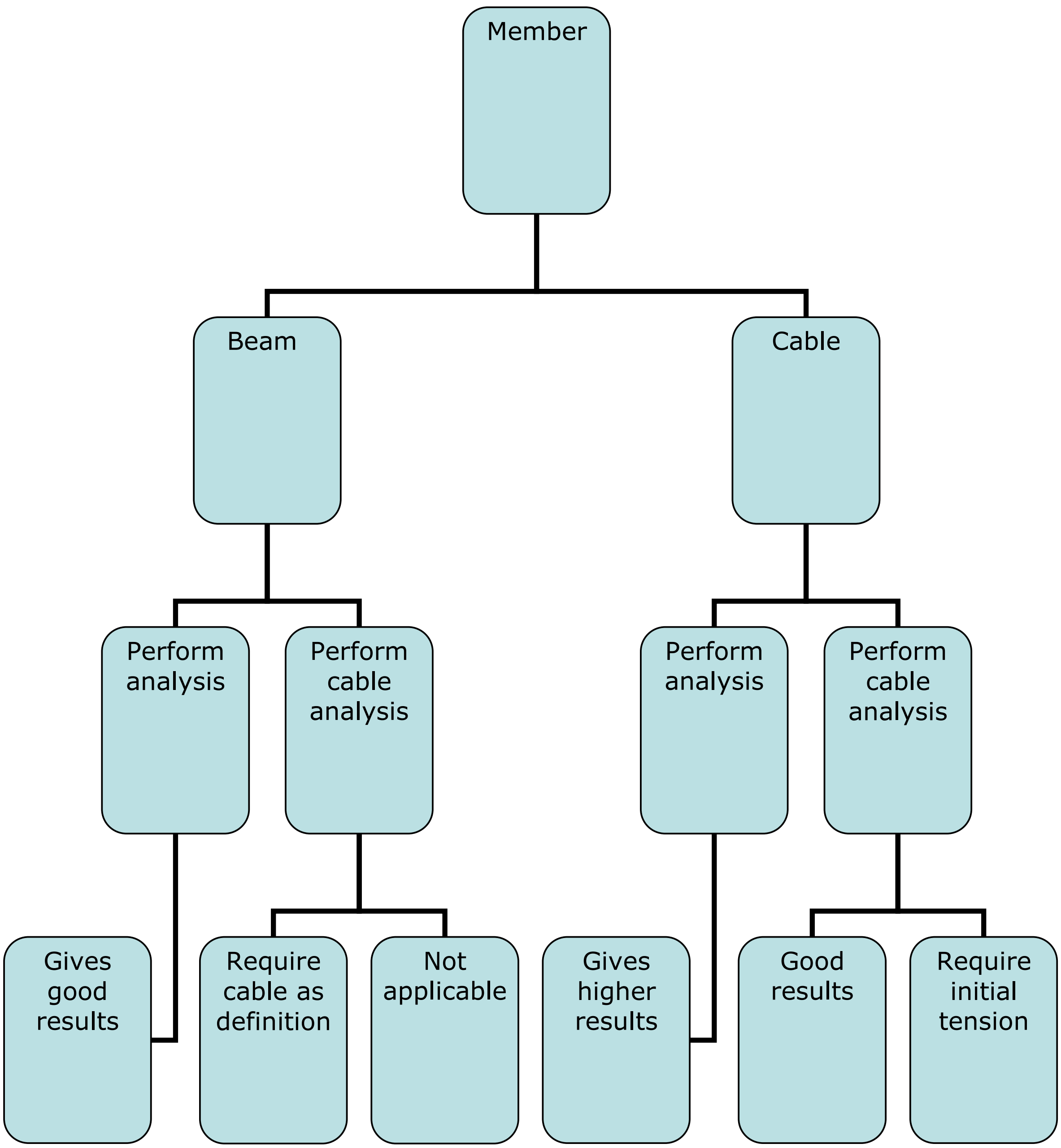


Figure-3.16 Applicability of staad-pro for analysis

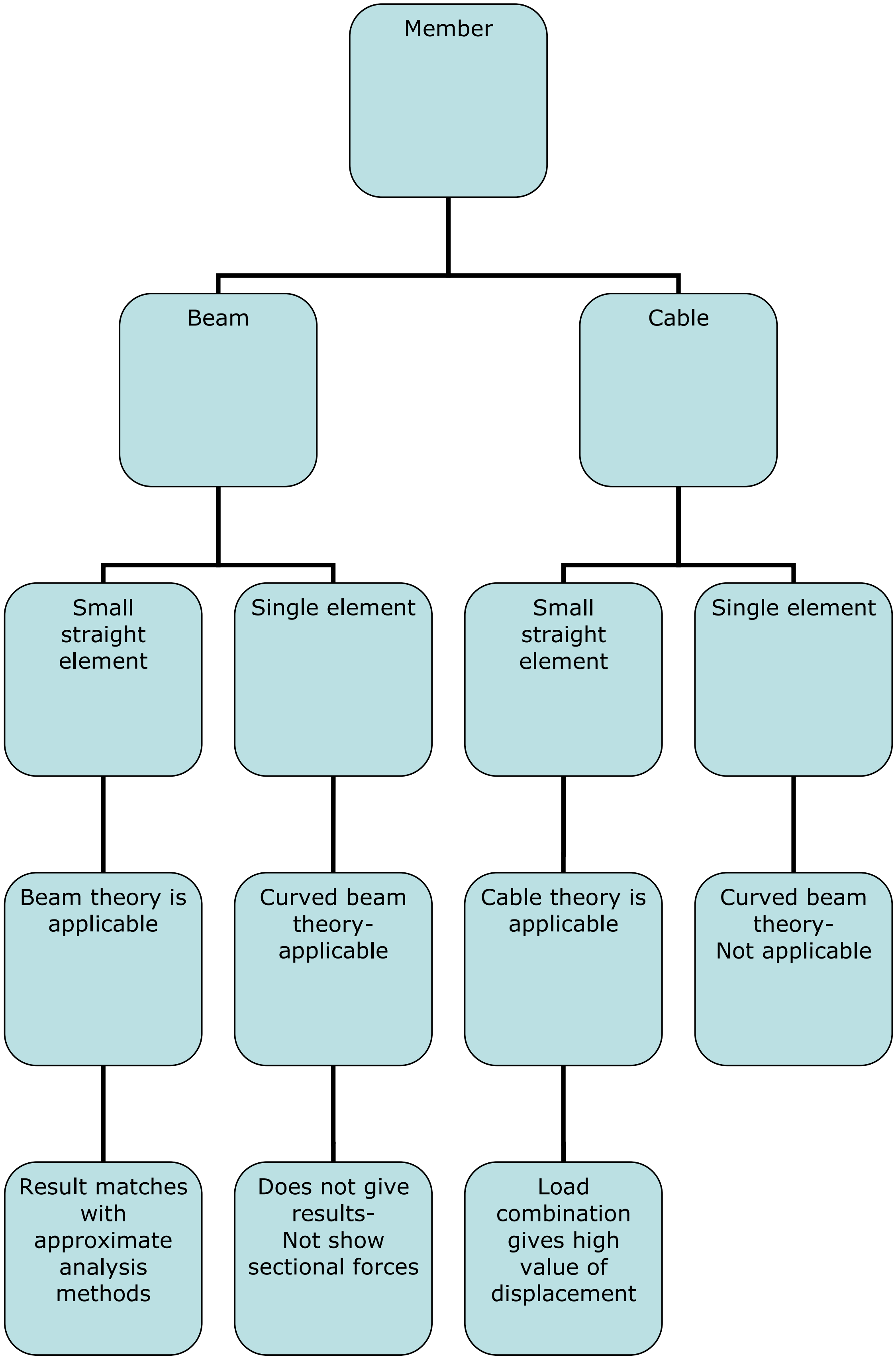


Figure-3.17 various theories applicable for analysis

AS far as cable structure is concern, there are different approaches to model the cable structure as follows:

(1) Beam made of Small straight elements

(2) Beam made of only one member

(3) Cable made of small straight elements

3.8.1 Beam made of small straight elements

As for singly curved cable structure, as such there is no initial tension is required so, the cable is defined as a beam-made of small straight segments.

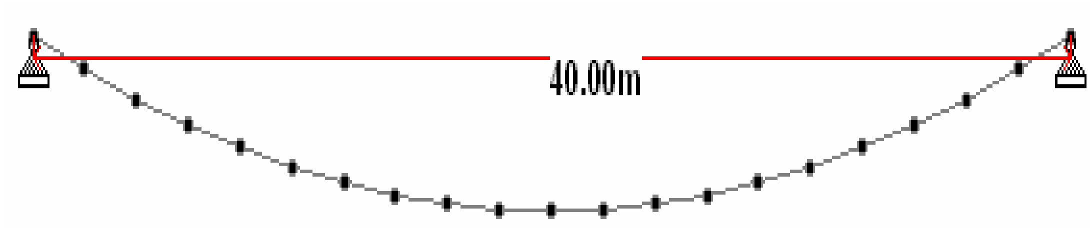


Figure 3.18- Beam made of small straight elements

3.8.2 Beam made of only one element-Curved beam theory

Cable is also defined as a single element in STAAD-Pro using curved beam theory.

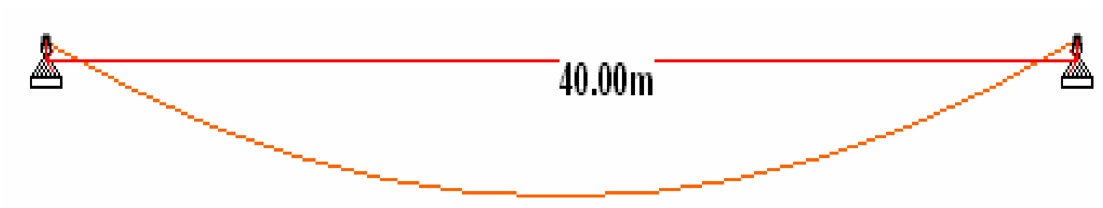


Figure 3.19- Beam made of only one element

3.8.3 Cable made of small straight elements

As for doubly curved cable structure, we have to provide initial tension as per calculation. So cable is defined as a cable-made of small straight segments.

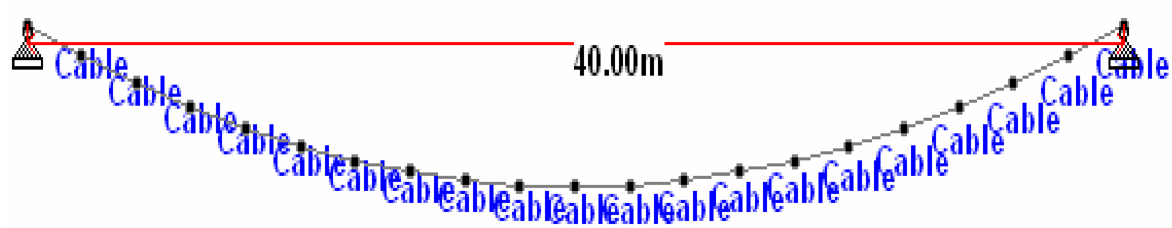


Figure 3.20- Cable made of small straight elements

3.8.4 Example of singly cable structure

DATA:

Width of cable structure: 40 m

Sag of structure: 4.0 m

Total load (DL+LL)-acting on cable: 3.25 kN / m

Table 3.1 Comparisons of maximum forces in single cable structure

Model	Type of cable structure	Axial force (kN)	Horizontal reaction (kN)	Vertical reaction (kN)
Beam made of Small straight elements	Singly curved	-177.063	164.073	66.69
Beam made of only one member	Singly curved	-----	164.073	66.69
Cable made of small straight elements	Singly curved	------	40.50	20.02

Comparing the different models with approximate analysis, the beam made of small straight element gives good results for singly suspended cable structure.

3.8.5 Example of doubly cable structure

DATA:

Span of cable structure: 40 m

Total load acting on bottom cable: 3.25 kN / m

Axial tension provided in top cable: 262.50 kN

Axial tension provided in bottom cable: 87.51 kN

Sag of each cable: 4 m

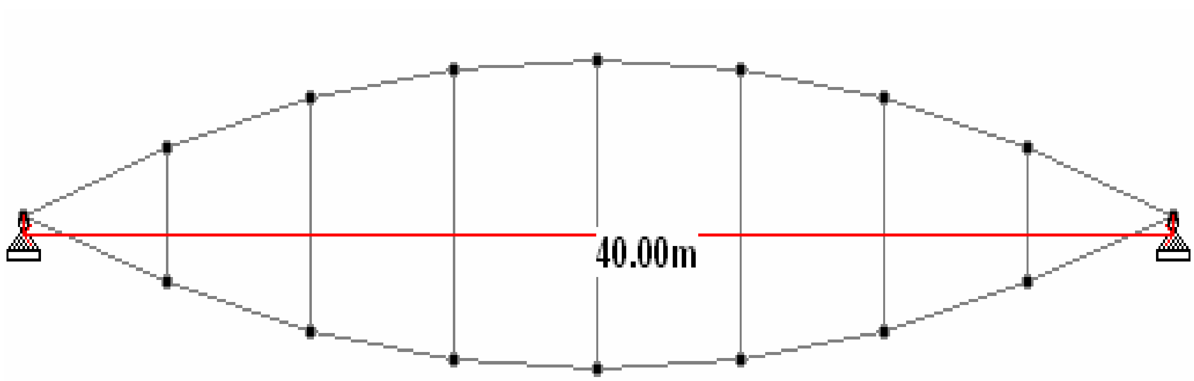


Figure 3.21- Double curved cable structure

Table 3.2 Comparisons of maximum forces in double cable structure

Model	Type of cable structure	Axial force (kN)	Horizontal reaction (kN)	Vertical reaction (kN)
Beam made of Small straight elements	Doubly curved	-116.262 (BC) 109.713 (TC)	2.874	67.045
Cable made of small straight elements	Doubly curved	-262.33 (BC) -89.266 (TC)	330.20	66.722

Comparing the two models with approximate analysis the cable made of small straight element gives good results for doubly curved cable structure.

3.9 SUMMARY

From the comparative study of different models, it is observed that for singly suspended cable structure, Beam made of small straight elements gives accurate results i.e. axial forces, horizontal and vertical reactions. Beam made of only one member theory (curved beam) is not much applicable since it doesn't show any sectional forces and it only shows reactions at supports. Cable made of small straight elements system gives appropriate results for double layer cable. To model double layer cable entire structural system has been divided into two parts (1) Roof structure module made of steel cable (2) supporting structure module made of R.C.C. To get effective convergence criteria and subsequently iteration process

4. ANALYSIS, DESIGN AND DETAILING OF CABLE SUSPENDED ROOF STRUCTURES

4.1 GENERAL

Analysis and design of a cable suspended roof structure require good understanding of the behavior of cable systems as well as familiarity with computer program. In this chapter, analysis, design and detailing methodology of cable structure is described.

Analysis and design of a cable suspended roof structure can be usually divided into the following steps:

a) Choice of cable system
b) Form finding
c) Analysis
d) Design of element sizes and connections
e) Construction

4.1.1 Choice of cable system

Following factors are considered during choice of cable system:

- Architectural requirements
- Span
- Availability of skilled labor
- Cost

4.1.2 Form finding

The form finding process means selection of appropriate shape decision. The main objective of form finding method is to create a model of the structure form such that its geometry satisfies the requirements of form (shape) and equilibrium can be found. An iterative process is required to obtain a general solution of form finding. One of them is force-density method. Force-density refers to the force to length ratio of an element. An element is defined as the cable member between two nodes while a node is the connection at which two cables intersect.

4.1.3 Analysis

In analysis process, it is important that the structure is tested under the different possible loading combinations. Primary loads are dead load, live load, wind load and earthquake load. Analysis of the structure under static and dynamic loading should also be performed. As such cable system is light weight structure so earthquake is not the major issue. So only static seismic analysis carried out for analysis and dynamic seismic analysis is ignored while for wind static and dynamic analysis is carried out.

4.1.4 Design

After analysis has been completed, design of structure commences. As such there is no special code for the design of cable structure. The general methodology for the design and construction of the cable structure shown in Fig. 4.1

4.2 PRILIMINARY DATA FOR ANALYSIS

As such to start with the problem preliminary data considered as follows:

DATA:

Location:	Rajkot
Width of structure:	40.0 m
Length of structure:	60.0 m
Height of structure:	18.0 m
Sag of structure:	4.0 m
Seismic zone:	III
Basic wind speed:	39.0 m/s
C/C spacing between two columns:	3.0 m
Width of column:	0.30 m
Depth of column:	0.60 m
Diameter of cable:	0.05 m
Depth of foundation:	3.0 m
Type of footing:	Isolated
Soil strata:	Rocky strata
Soil bearing capacity:	350 kN / m^2
Type of cladding:	Fabric

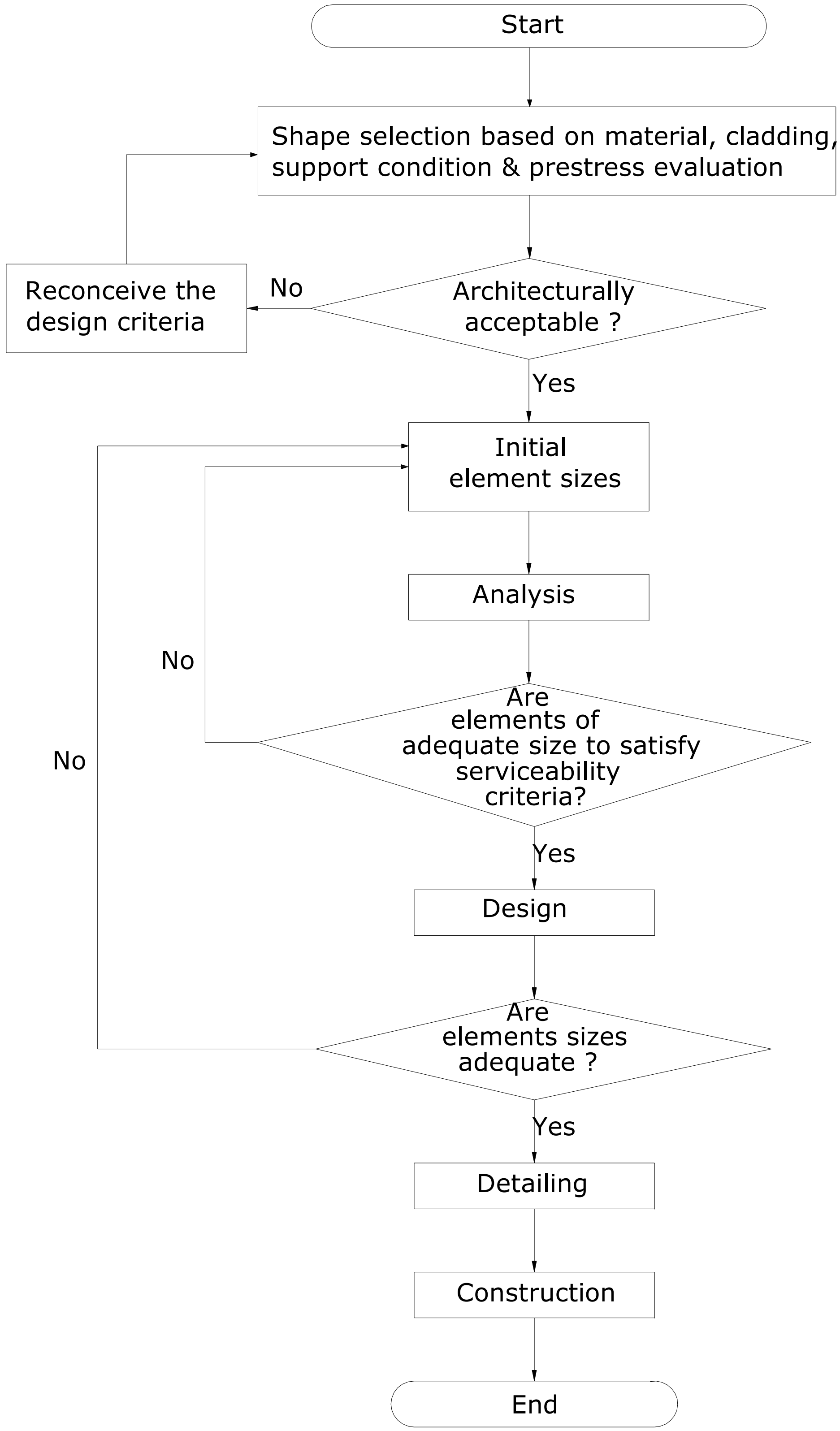


Figure 4.1 Flow chart for general design approach of cable structure

4.3 LOAD CALCULATION

4.3.1 Single curved cable

4.3.1.1 *Dead Load:* 0.33 kN / m^2

(Assumed on the basis of that dia of cable =0.1 m initially).

C/C distance between two columns: 3.0 m

Load on cable: 1.0 kN/m

4.3.1.2 Live Load:

(As per TABLE-2) IS: 875-PART (II) - curved roof more than 10 degree

As per calculation: - $0.75-0.52Y^2$

$Y= (h/l)^2$

$= (4/40)^2 = 0.01$

$= 0.75-0.52(0.01)$

$= 0.7448$ kN / m^2

C/C distance between two columns: 3.0 m

Load on cable: 2.2344 kN/m

4.3.1.3 Wind Load: [Appendix: A]

Table 4.1 Wind load for single curved cable suspended roof structure

Load condition	Pressure or Suction	Long wall (kN/m²)	Short wall (kN/m²)	Roof (kN/m²)
Static	Pressure	1.03	1.03	0.086
	Suction	-0.86	-0.94	-1.12
Dynamic	Pressure	0.72	0.73	------
	Suction	-0.52	-0.62	-0.83

4.3.1.4 Earthquake Load: [Appendix: A]

Total base shear: 817.00 kN

4.3.2 Double curved cable

4.3.2.1Dead Load: 0.283 kN / m^2

C/C distance between two columns: 3.0 m

Load on cable: 0.85 kN/m

(Assumed on the basis of that dia of cable =0.05 m initially).

4.3.2.2 Live Load:

(As per TABLE-2) IS: 875-PART (II) - curved roof more than 10 degree

As per calculation: - $0.75\text{-}0.52Y^2$

$Y = (h/l)^2$

$= (4/40)^2 = 0.01$

$= 0.75\text{-}0.52(0.01)$

$= 0.7448$ kN / m^2

C/C distance between two columns: 3.0 m

Load on cable: 2.2344 kN/m

4.3.2.3 Wind Load: [Appendix: A]

Table 4.2 Wind load for double curved cable suspended roof structure

Load condition	Pressure or Suction	Long wall windward (kN/m^2)	Long wall leeward (kN/m^2)	Roof (kN/m^2)
Static	Pressure	0.26	----	----
	Suction	-1.12	-0.94	-1.12
Dynamic	Pressure	0.82	----	------
	Suction	----	-0.62	-0.83

4.3.2.4 Earthquake Load: [Appendix: A]

Total base shear: 817 kN

4.3.3 Calculation of sitting gallery:

Self Weight of 100 mm thick slab = 0.1 X 25

= 2.5 kN/m^2

Live load = 5.0 kN/m^2

Floor finish = 1.0 kN/m^2

Total load on slab panel = 8.5 kN/m^2

UDL on each slab panel = 8.5 kN/m

Reactions = 8.5 X 3/2

= 12.75 kN

Weight of one step = 0.43 X 0.1 X 1.5 X 25

	=	1.6125 kN
Total	=	14.36 kN

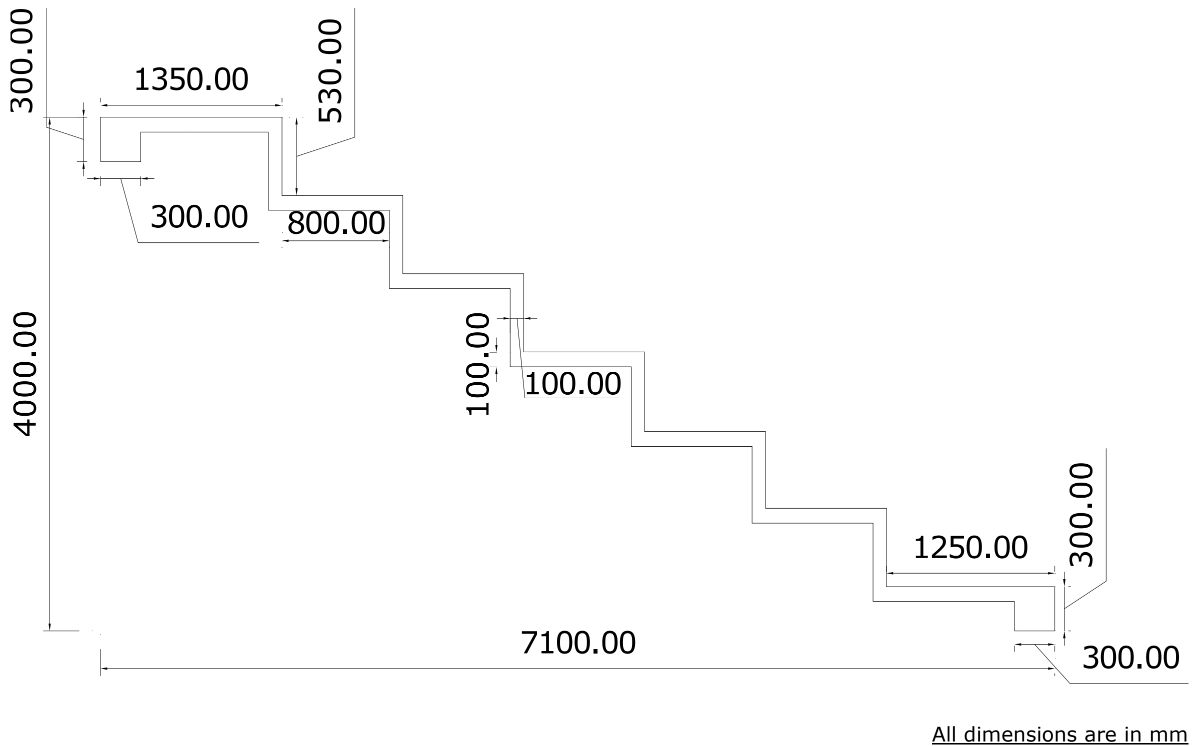


Figure 4.2 Elevation of sitting gallery

No. of point load on Entire beam	=	7 No.
Total load on beam	=	14.36 X 7
	=	100.53 kN (outer)
	=	201.07 kN (Inner)
Load/m of beam	=	(100.53/7.63)
	=	13.17 kN/m (outer)
	=	26.35 kN/m (Inner)
Self weight of beam	=	0.3 X 0.6 X 25
	=	4.50 kN/m
Total UDL on inner beam	=	30.85 kN/m
Total UDL on outer beam	=	17.67 kN/m

4.4 LOAD COMBINATION

Cable structure is the combination of steel and R.C.C. so here load combination is selected for roof as per IS 800:1984 and for supporting structure the load combinations for limit state of collapse as per IS 875 (Part-5): 1987 given in Table-4.1. The loads are considered as calculated above.

Table 4.3 Load combinations

Load combination	Load factors			
	DL	LL	Wind	Earthquake
COMB 1	1.0	1.0	-	-
COMB 2	1.0	1.0	1.0 (x)	-
COMB 3	1.0	1.0	-1.0 (x)	-
COMB 4	1.0	1.0	1.0 (z)	-
COMB 5	1.0	1.0	-1.0 (z)	-
COMB 6	1.0	-	1.0 (x)	
COMB 7	1.0	-	-1.0 (x)	
COMB 8	1.0	-	1.0 (z)	
COMB 9	1.0	-	-1.0 (z)	
COMB 10	1.5	1.5	-	-
COMB 11	1.2	1.2	1.2 (x)	-
COMB 12	1.2	1.2	-1.2 (x)	-
COMB 13	1.2	1.2	1.2 (z)	-
COMB 14	1.2	1.2	-1.2 (z)	-
COMB 15	1.5	-	1.5 (x)	-
COMB 16	1.5	-	-1.5 (x)	-
COMB 17	1.5	-	1.5 (z)	-
COMB 18	1.5	-	-1.5 (z)	-
COMB 19	0.9	-	1.5 (x)	-
COMB 20	0.9	-	-1.5 (x)	-
COMB 21	0.9	-	1.5 (z)	-
COMB 22	0.9	-	-1.5 (z)	-
COMB 23	1.2	1.2	-	1.2 (x)
COMB 24	1.2	1.2	-	-1.2 (x)
COMB 25	1.2	1.2	-	1.2 (z)
COMB 26	1.2	1.2	-	-1.2 (z)
COMB 27	1.5	-	-	1.5 (x)
COMB 28	1.5	-	-	-1.5 (x)
COMB 29	1.5	-	-	1.5 (z)

COMB 30	1.5	-	-	-1.5 (z)
COMB 31	0.9	-	-	1.5 (x)
COMB 32	0.9	-	-	-1.5 (x)
COMB 33	0.9	-	-	1.5 (z)
COMB 34	0.9	-	-	-1.5 (z)

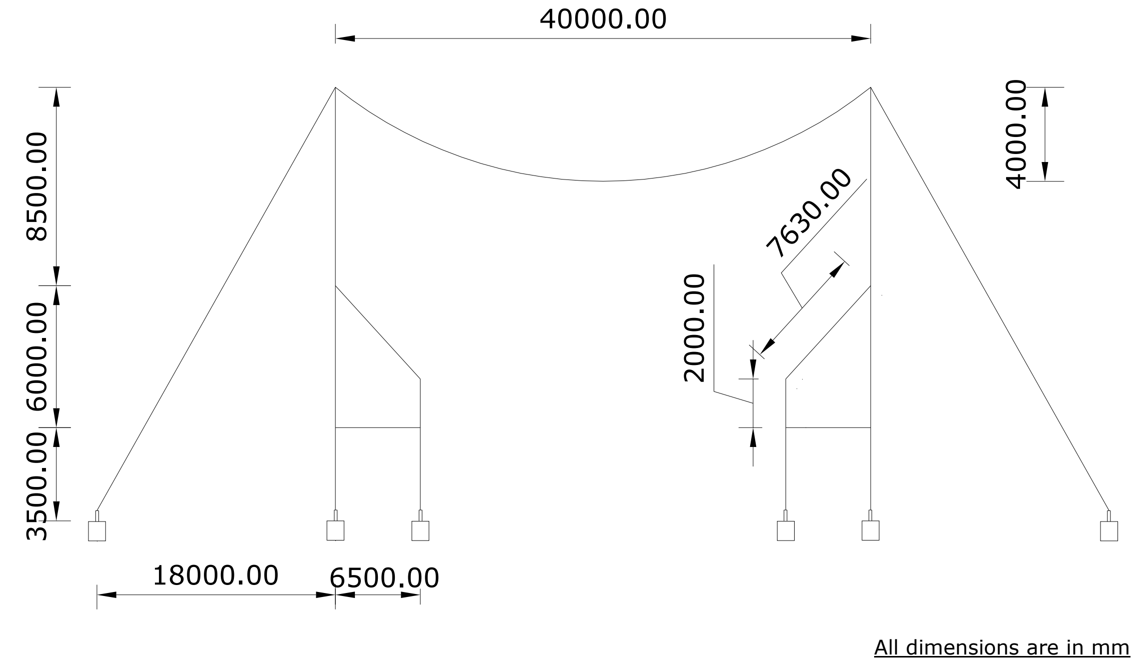


Figure 4.3 Elevation of single layer cable

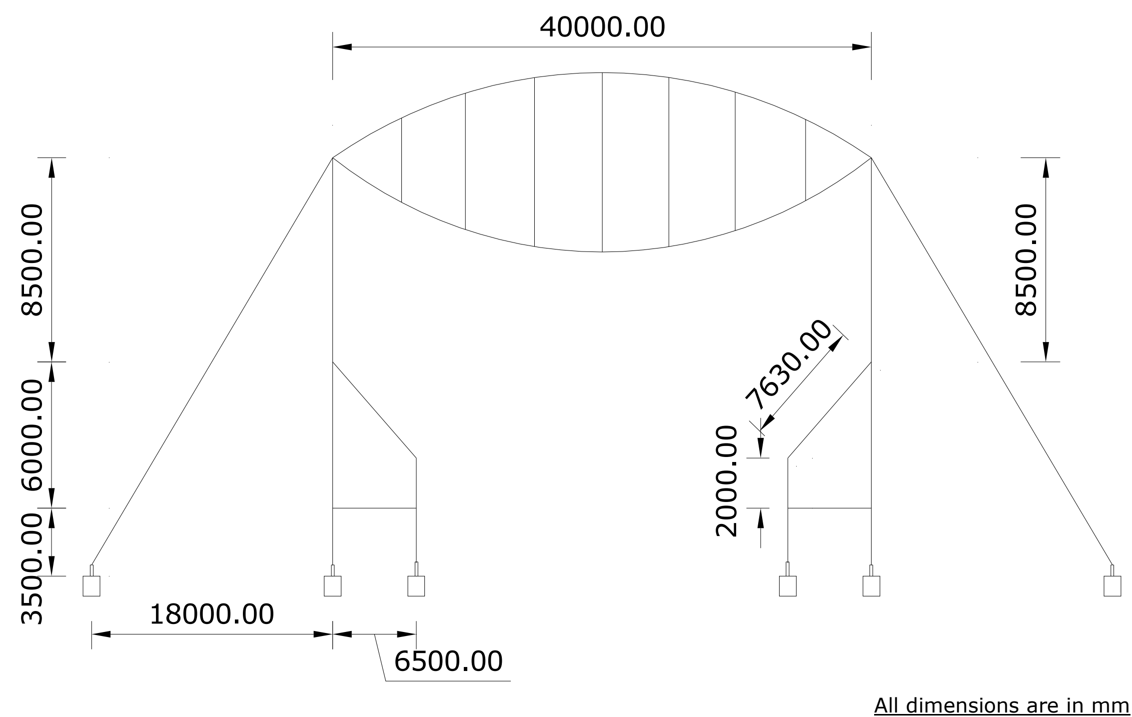


Figure 4.4 Elevation of double layer cable

4.5 ANALYSIS

After performing analysis of cable structure, the results are presented in tabulated manner below. The cable analysis is carried out using STAAD-PRO-2005.

4.5.1 Single layer cable:

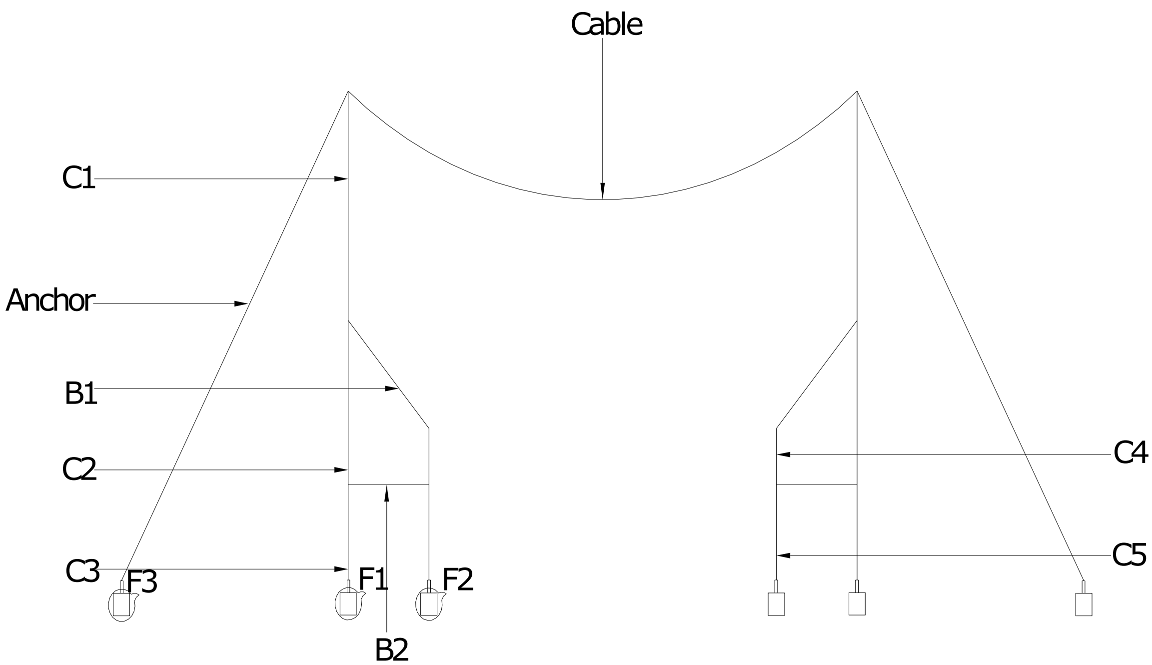


Figure 4.5 Identity of single layer cable structure

Table 4.4 Analysis results of single layer cable structure

Member Identity	Length of member (m)	Max axial forces (kN)	Min axial forces (kN)	Max moment (kNm)	Min moment (kNm)
Cable	41.06	----	-373.55	----	----
Anchor	25.46	----	-563.40	----	----
C1	8.50	567.13	-233.01	153.21	-119.07
C2	6.00	687.17	-128.12	203.94	-194.12
C3	3.50	719.25	-140.03	89.33	-78.59
C4	2.00	228.16	99.45	155.46	-155.46
C5	3.50	250.44	72.99	88.40	-66.21
B1	7.63	171.68	-74.41	155.46	-168.97
B2	6.50	----	-67.01	106.80	-101.71

4.5.2 Double layer cable:

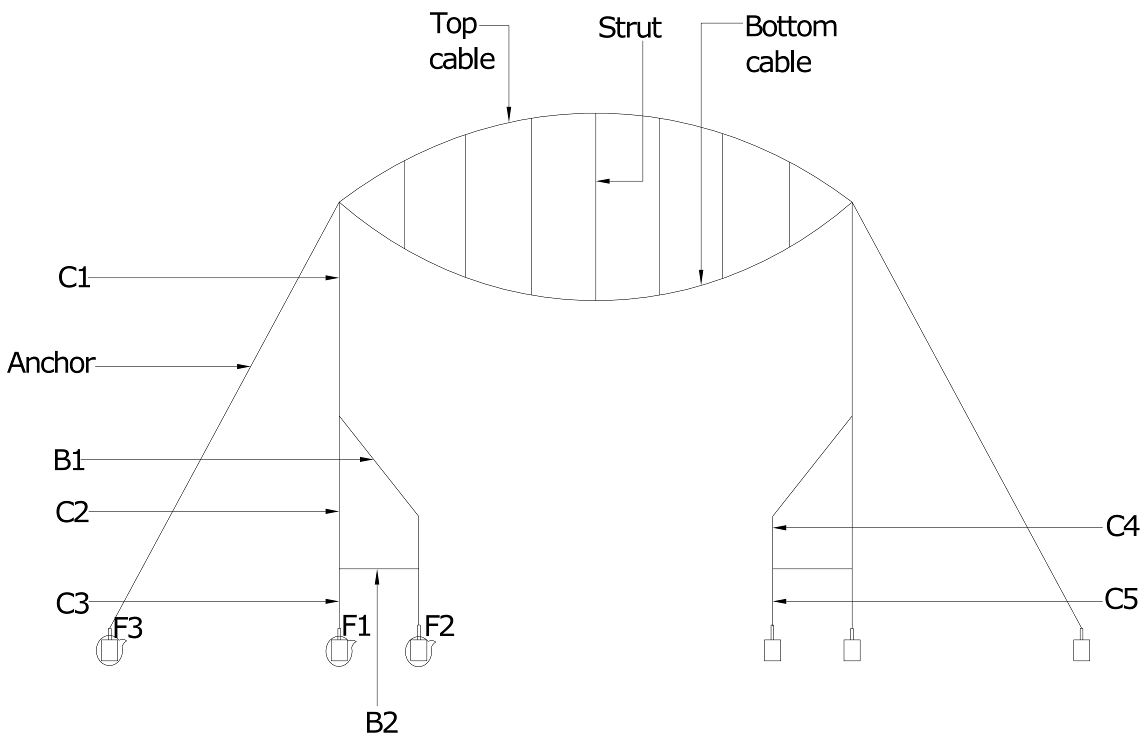


Figure 4.6 Identity of double layer cable structure

Table 4.5 Analysis results of double layer cable structure

Member Identity	Length of member (m)	Max axial forces (kN)	Min axial forces (kN)	Max moment (kNm)	Min moment (kNm)
Top cable	41.06	----	-169.08	----	----
Bottom cable	41.06	----	-513.62	----	----
Strut	8.00	16.00	----	----	----
Anchor	25.46	----	-1110.00	----	----
C1	8.50	992.26	913.08	110.58	0.00
C2	6.00	1150.00	1090.00	190.33	-101.23
C3	3.50	1210.00	1130.00	62.83	-76.26
C4	2.00	256.28	180.74	----	-188.25
C5	3.50	295.31	178.65	50.78	-69.81
B1	7.63	209.04	-70.18	188.25	-161.20
B2	6.50	----	-68.39	110.58	-76.66

4.5.3 Deflection:

Dia of cable: 45 mm, Dia of anchor: 71 mm

Table 4.6 Comparison of deflection between single & double layer cable structure

Structural system	Max vertical deflection (mm)	Allowable deflection (mm)	Max horizontal deflection (mm)	Allowable deflection (mm)	Remarks
Single layer cable	642.107	123.07	180.460	55.38	-----
Double layer cable	120.899	123.07	53.093	55.38	O.K

4.5.4 Reactions:

Table 4.7 Reactions at footing

Structural system	Footing Identity	Horizontal FX (kN)	Vertical FY (kN)	Moment MZ (kNm)
Single layer	F1	25.811	719.251	-81.765
		-34.135	-140.034	71.021
		-41.167	85.538	78.594
		32.842	493.678	-89.338
	F2	2.013	214.443	-14.215
		31.876	72.992	-87.853
		-29.525	158.728	66.217
		32.311	128.686	-88.407
	F3	398.380	-398.398	0.078
		-374.888	-374.910	-0.105
		-162.386	162.394	-0.034
		398.380	-398.398	0.078
Double layer	F1	24.462	1.21E 3	-76.266
		-38.324	1.15E 3	62.839
		-38.324	1.15E 3	62.839
		24.462	1.21E 3	-76.266
	F2	-25.609	295.315	50.783
		19.759	196.466	-69.814
		-25.609	295.315	50.783

		19.759	196.466	-69.814
	F3	-745.152	-735.937	0.000
		-781.072	-771.857	0.000
		-745.152	-735.937	0.000
		-781.072	-771.857	0.000

4.6 DESIGN

4.6.1 Roof:

4.6.1.1 Cable:

Type: Spiral rope

Sizes available: 1 X 19, 1 X 37, 1 X 61, 1 X 91, 1 X 127, 1 X 169, 1 X 217

End fitting: Swaged socket

Modulus of Elasticity: Approx. 200000 N/mm^2

Strength is higher than any other type of cable of the same diameter.

Table 4.8 Cable design schedule

Member Identity	Length of member (m)	Rope dia. (mm)	Nominal diameter in outermost layer (mm)	Standard sectional area (mm^2)	Grade	Breaking load (kN)	Unitary mass (kg/m)
Top	41.06	25	5.00	373	ST1470	512.00	3.06
Bottom	41.06	45	5.04	1230	ST1470	1630.00	10.00
Anchor	25.46	71	4.83	3100	ST1470	3990.00	25.40

4.6.1.2 Strut:

Grade of steel: Yst 32

Permissible axial stress in tension: 190 N/mm^2

Table 4.9 Strut design schedule

Member Identity	Length of member (m)	Nominal dia of bore (mm)	Outside dia of bore (mm)	Class	Thk. (t) mm	Weight (kg/m)	Area of c/s (cm^2)	Radius of gyration (cm)
Strut	8.00	125.00	139.70	Light	4.50	15.00	19.10	4.78

4.6.2 Column:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 4.10 Column design schedule

Member Identity	Length of member (m)	Size (mmxmm)	Vertical steel (Nos.-dia)	Sp. Confi. hoops through out column (#, mm c/c)	Sp. Confi. Hoops up to length "lo" (#, mm c/c)	Length "lo" (mm)	Hoops beyond length "lo" (#, mm c/c)
C1	8.5	300 X 600	4- #16 +8- #12	------	#8,100	1370	#8, 200
C2	6.0	300 X 600	6- #16 +6- #12	------	#8,100	900	#8, 200
C3	3.5	300 X 600	6- #16 +6- #12	#8,100	------	-----	------
C4	2.0	300 X 600	6- #16 +6- #12	------	#8,100	600	#8, 200
C5	3.5	300 X 600	6- #16 +6- #12	#8,100	------	-----	------

4.6.3 Beam:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 4.11 Beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
B1	7.63	300 X 600	2- #25	2- #25
B2	6.50	300 X 600	2- #25	2- #25

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	150	1120	8	250	4790	8	150	1120
8	150	1120	8	250	3660	8	150	1120

4.6.4 Sitting gallery:

Grade of steel: Fe 415

Grade of concrete: M 20

Table 4.12 Sitting gallery beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
Beam	3.00	100 X 630	2- #10	2- #8

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	200	1200	8	250	600	8	200	1200

Table 4.13 Sitting gallery slab design schedule

Member Identity	Size (mm x mm)	Thickness (mm)	Main steel (Dia-Spc mm c/c)	Distribution steel (Dia-Spc mm c/c)
SLAB	900 X 3000	100	#8-225	#6-175

4.6.5 Footing:

Grade of steel: Fe 415

Grade of concrete: M 20

P.C.C thickness: 150 mm

P.C.C grade: 1:3:6

Soil bearing capacity: 350 kN/m^2

Table 4.14 Footing design schedule

Member Identity	P.C.C size (mm x mm)	Footing size (mm x mm)	End Thk. "t" mm	Overall Thk. "T" mm	Short bars (dia-mm-c/c)	Long bars (dia- mm-c/c)	Remark
F1	1670 X 1980	1370X1680	150	450	#16-125	#12-125	Isolated
F2	1370 X 1670	1070X1300	150	450	#16-125	#12-125	Isolated

4.6.6 Anchor block:

Grade of steel: Fe 415

Grade of concrete: M 25

Material: Epoxy grout

Skin friction coefficient: 0.4

No. of bore holes: 9

Table 4.15 Anchor block short column design schedule

Member Identity	Dia of bore (mm)	Length of bore (mm)	Vertical steel (Nos.-dia)	Hoops through out column (#, mm c/c)	Remark
F3	100	750	4- #10	#8,150	Short tension pile

Table 4.16 Anchor block slab design schedule

Member Identity	Size (mm x mm)	Thickness (mm)	Main steel (Dia-Spc mm c/c)	Distribution steel (Dia-Spc mm c/c)
SLAB	1000 X 1000	200	#16-100	#16-100

4.7 DETAILING

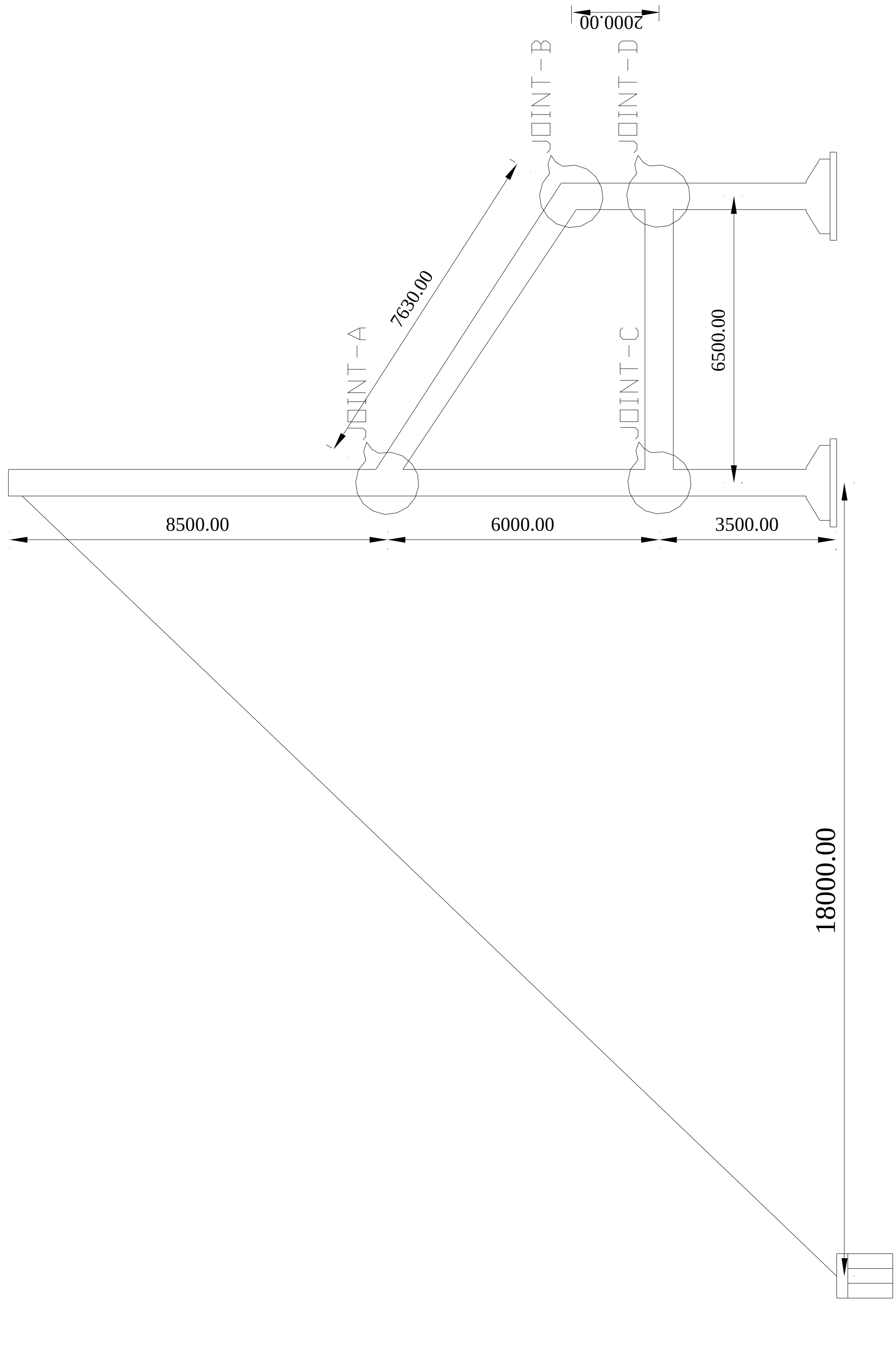


Figure 4.7 Structural system module for cable structural system

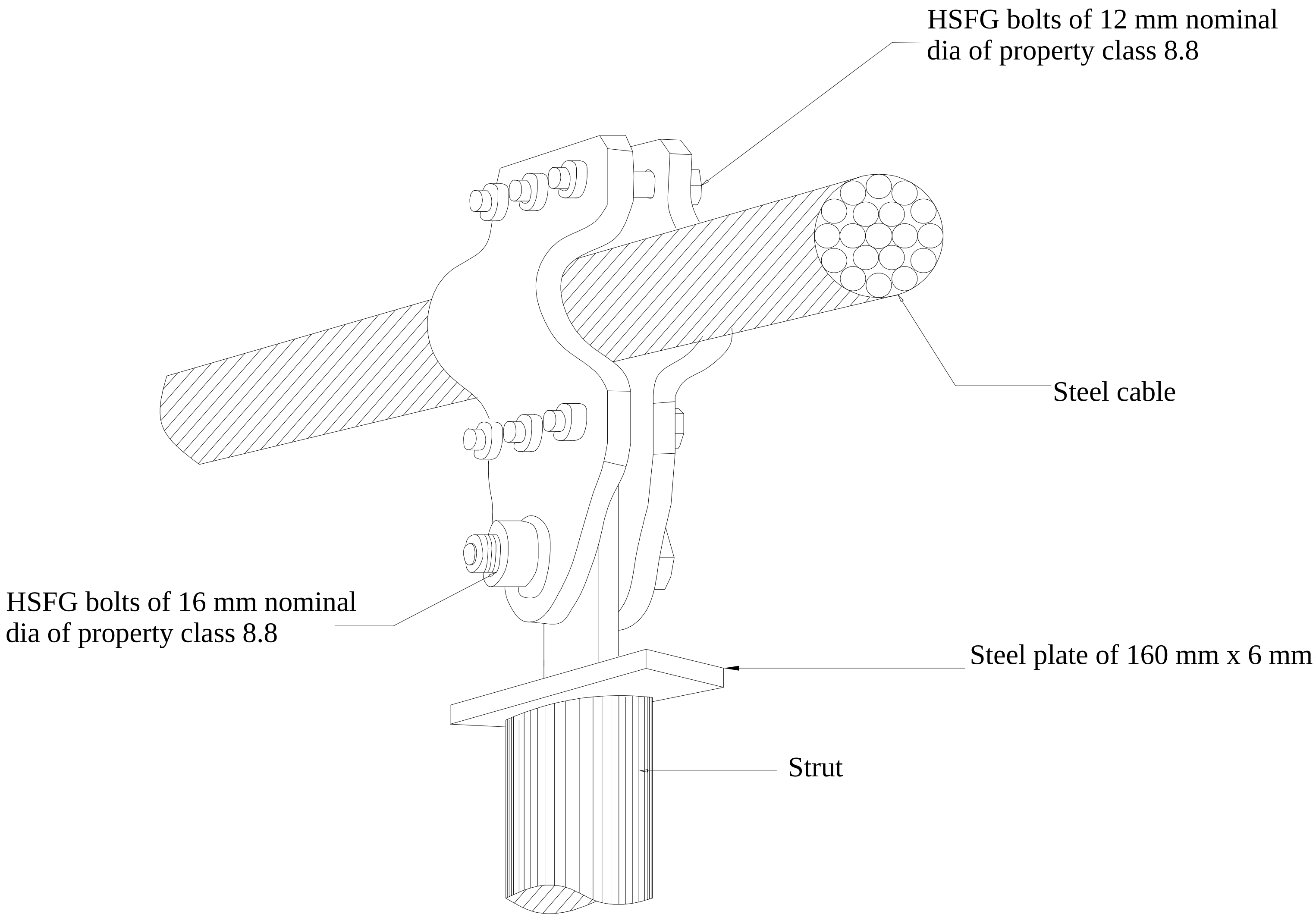


Figure 4.8 Cable strut connection

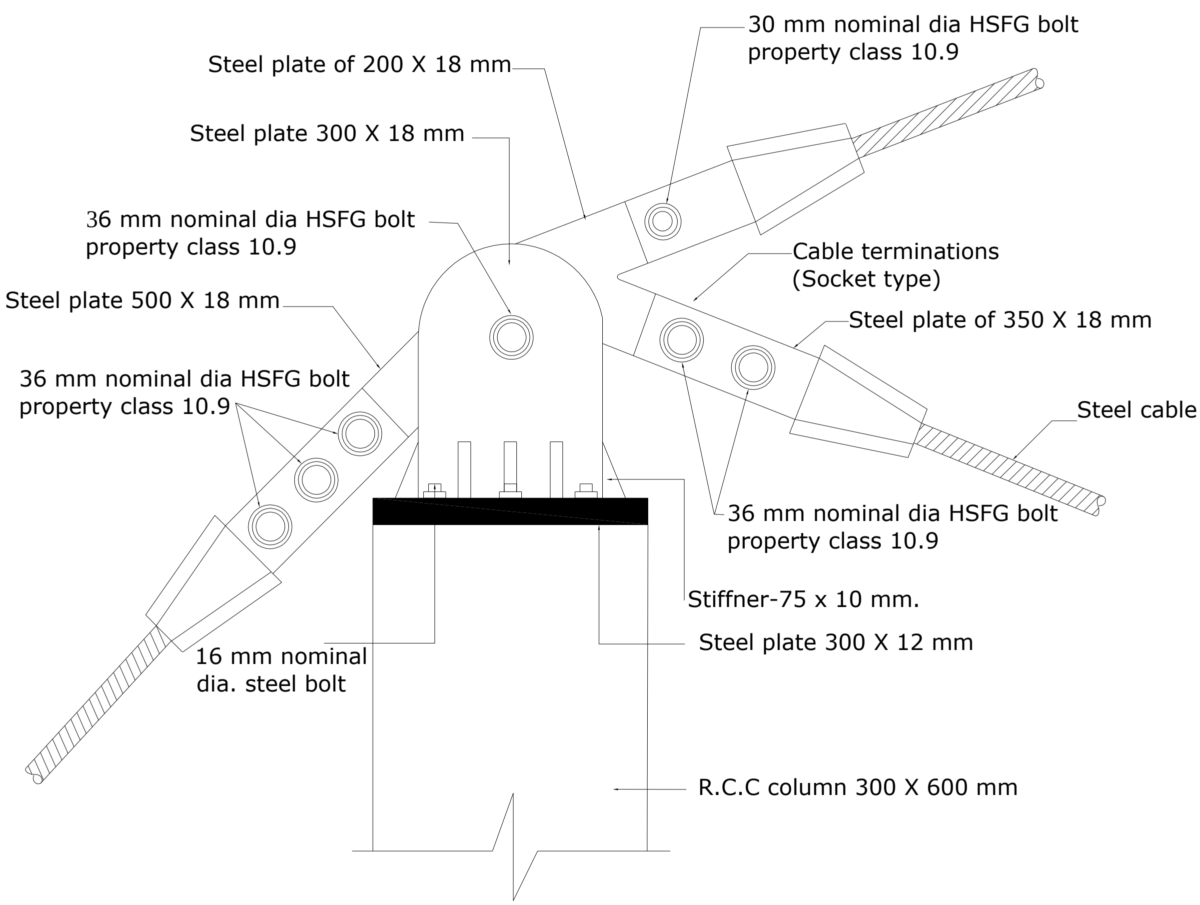


Figure 4.9 Elevation of cable-column connection (hinge connection)

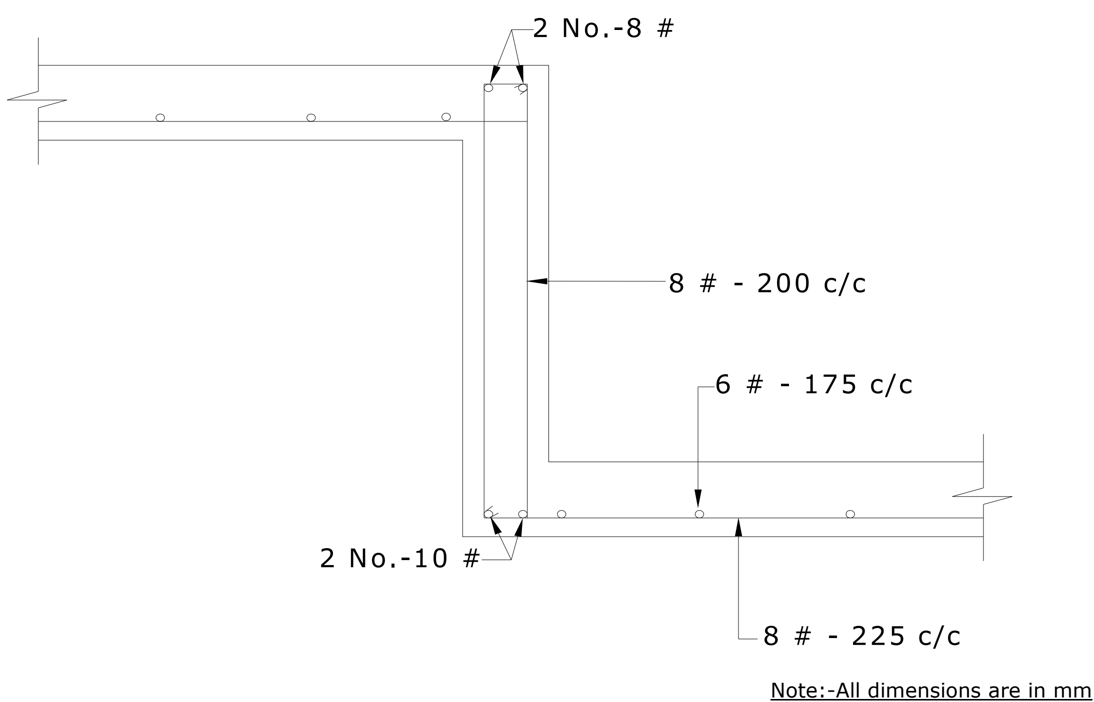


Figure 4.10 Detailing of sitting gallery beam-slab

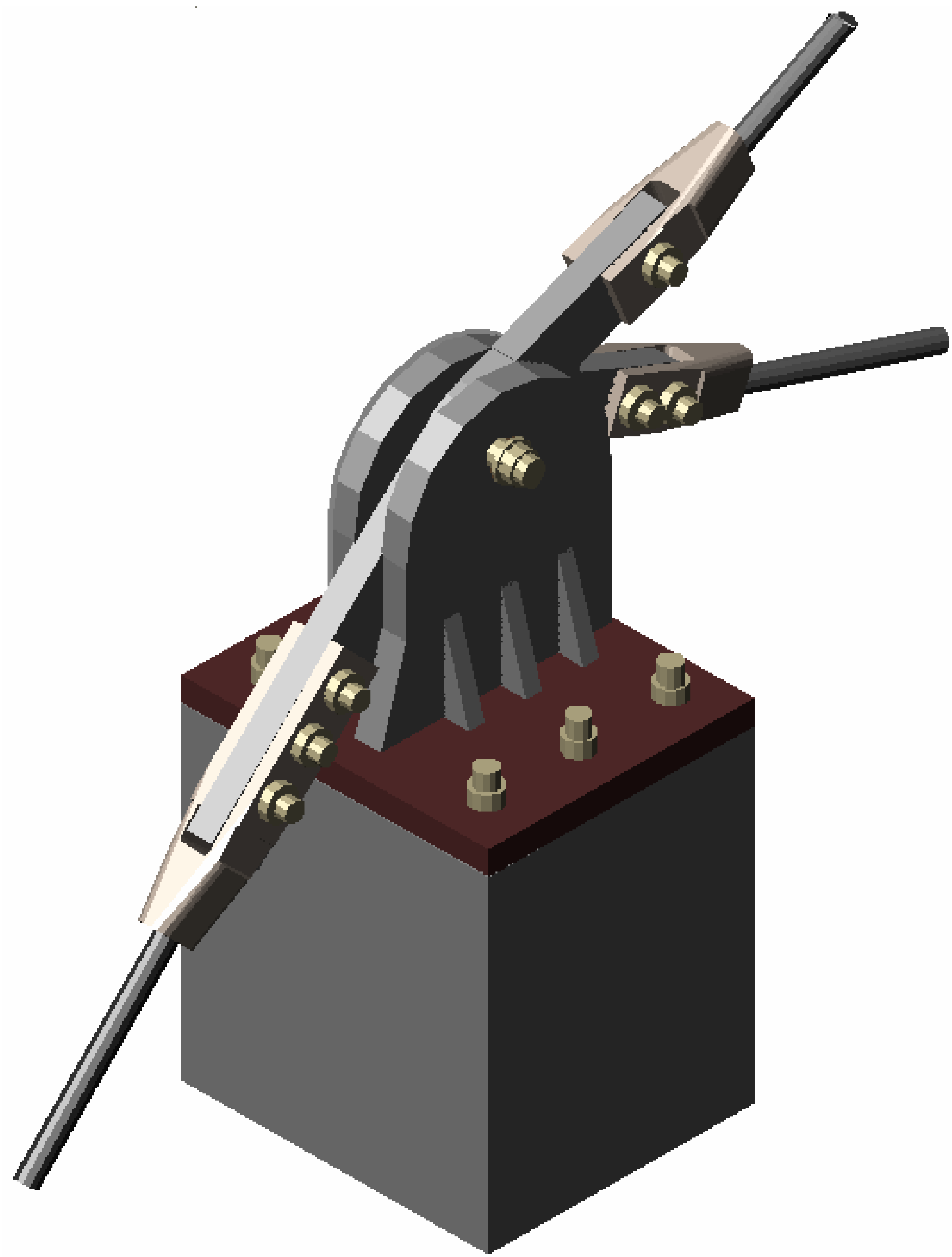


Figure 4.11 3d view of cable-column connection
(Hinge connection)

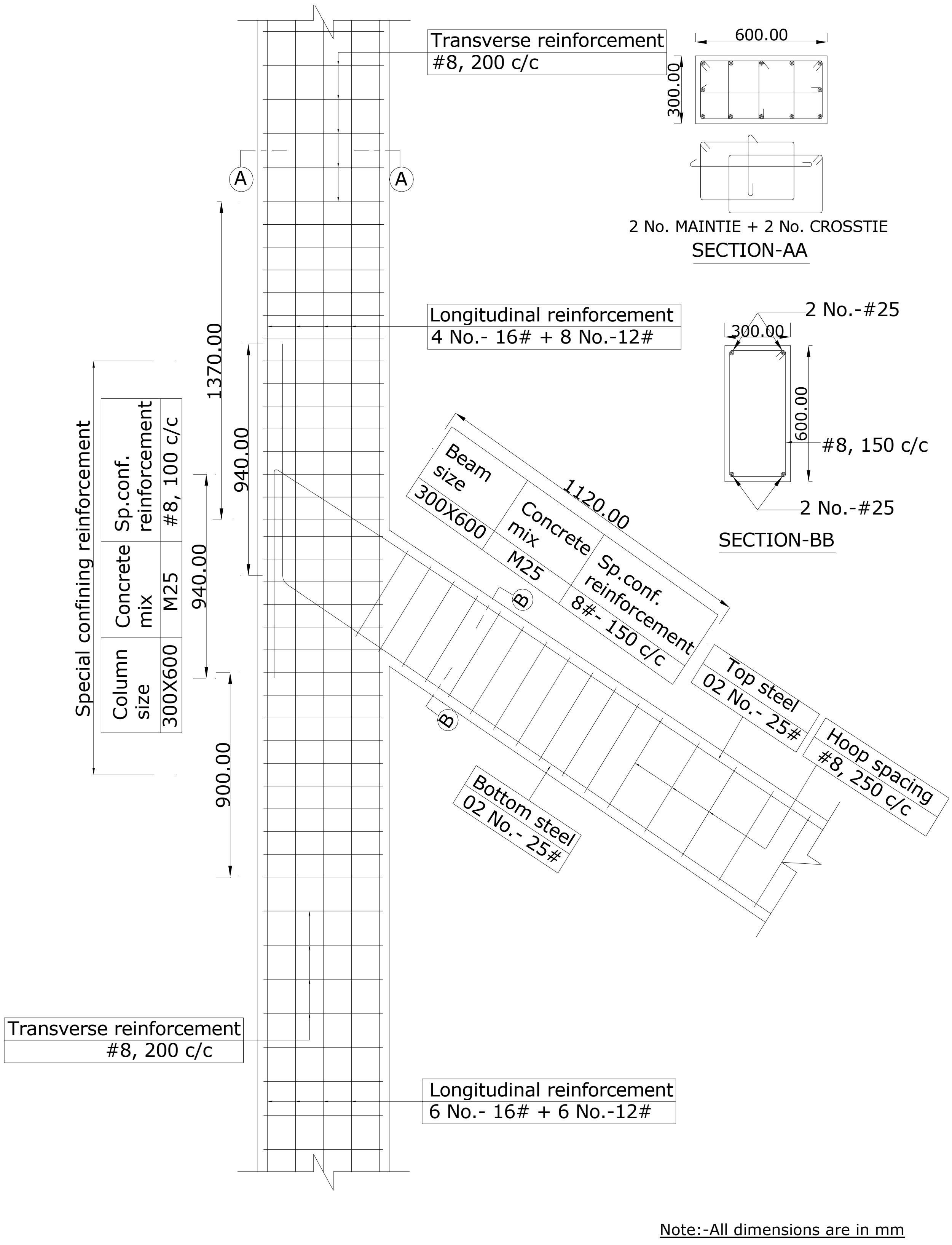


Figure 4.12 Beam-column junction (Joint-A)

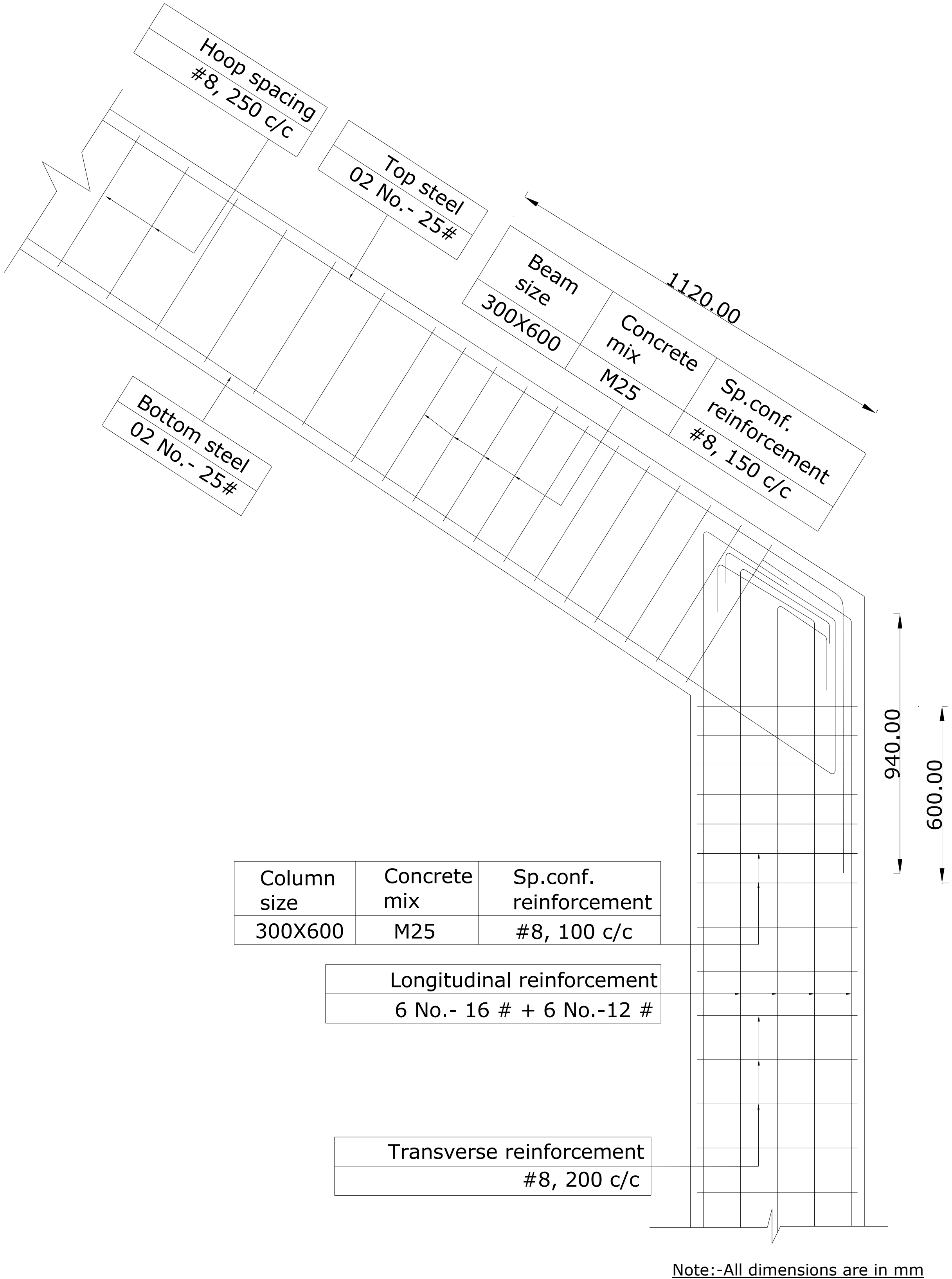


Figure 4.13 Beam-column junctions (Joint-B)

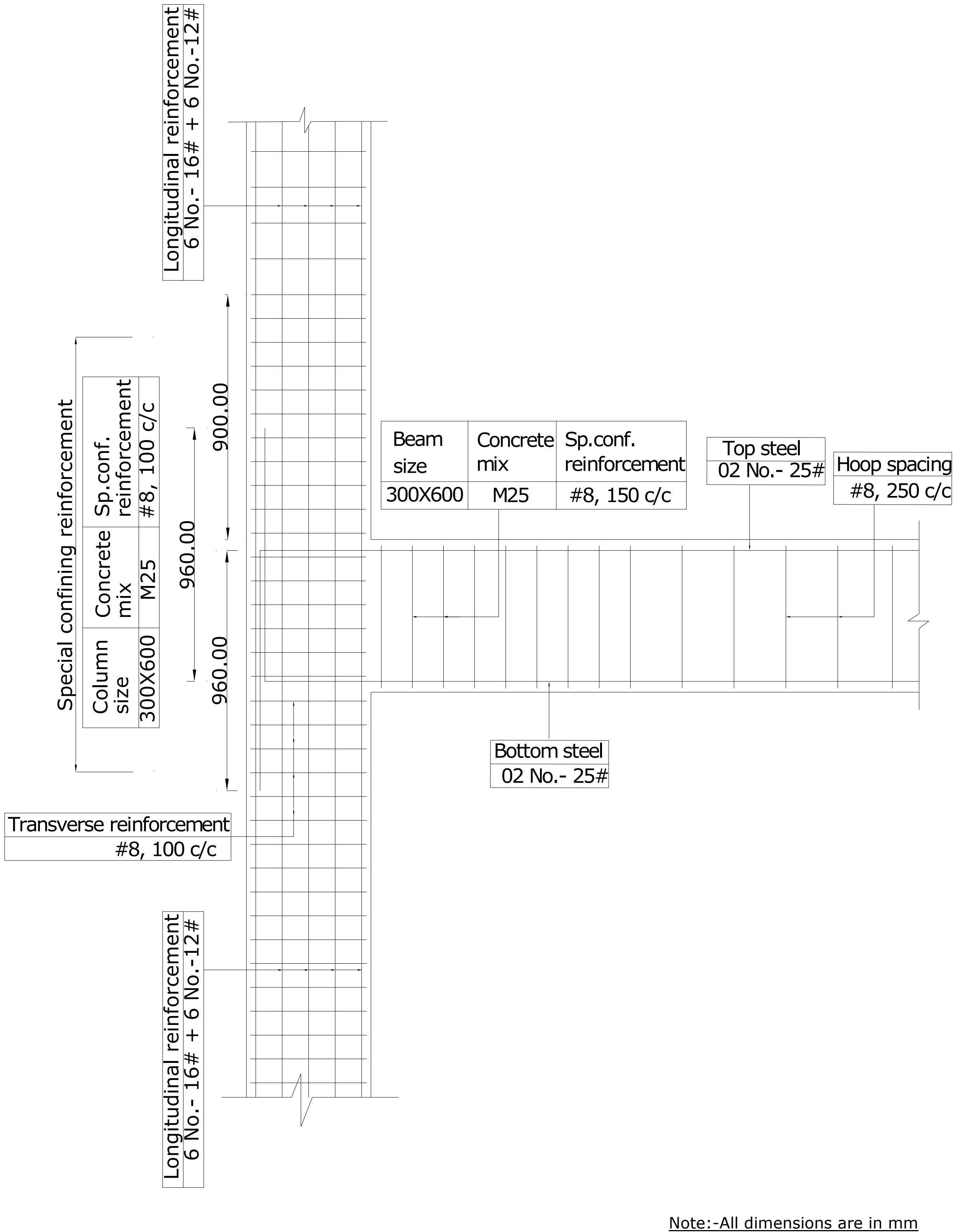
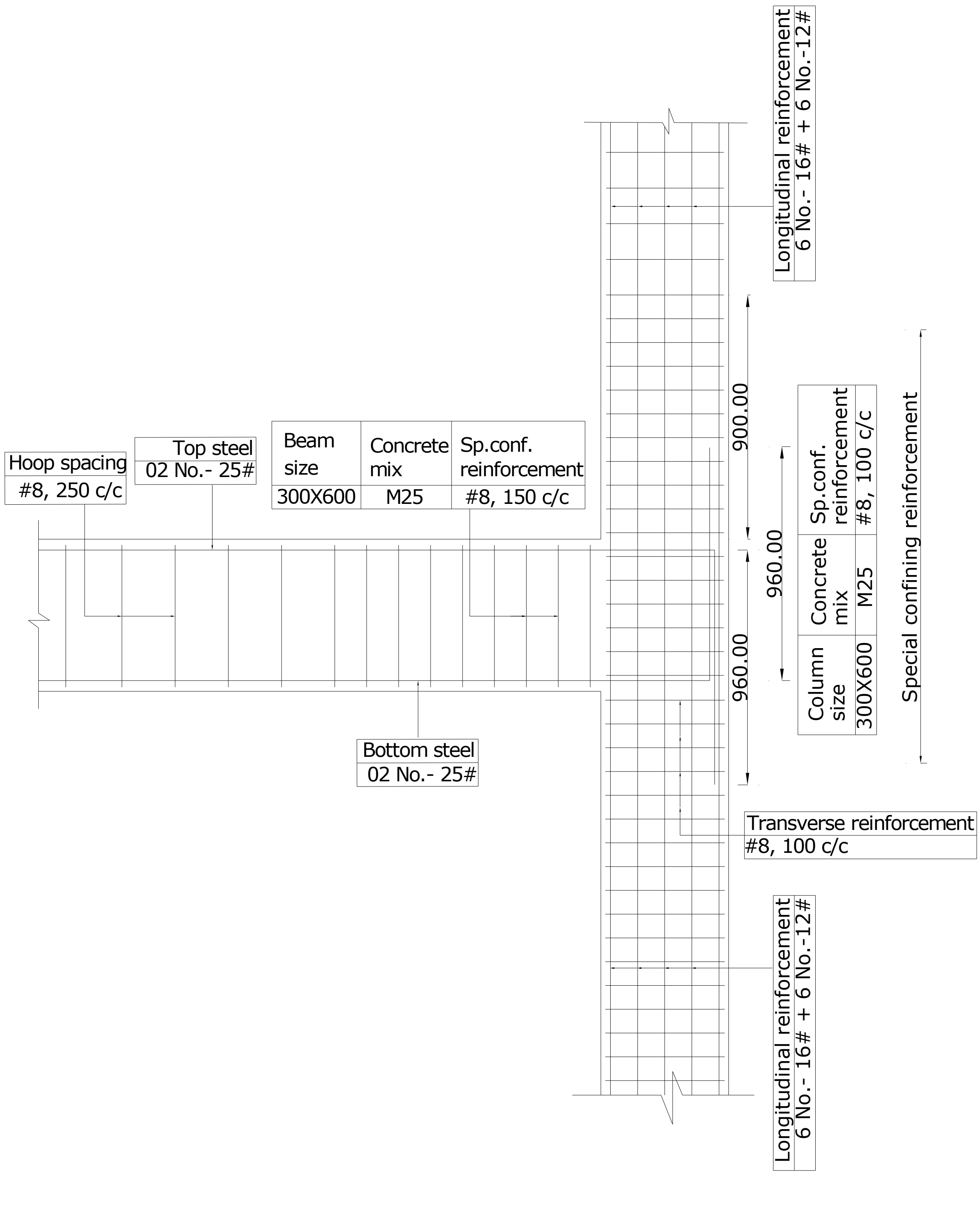


Figure 4.14 Beam-column junctions (Joint-C)



Note:-All dimensions are in mm

Figure 4.15 Beam-column junctions (Joint-D)

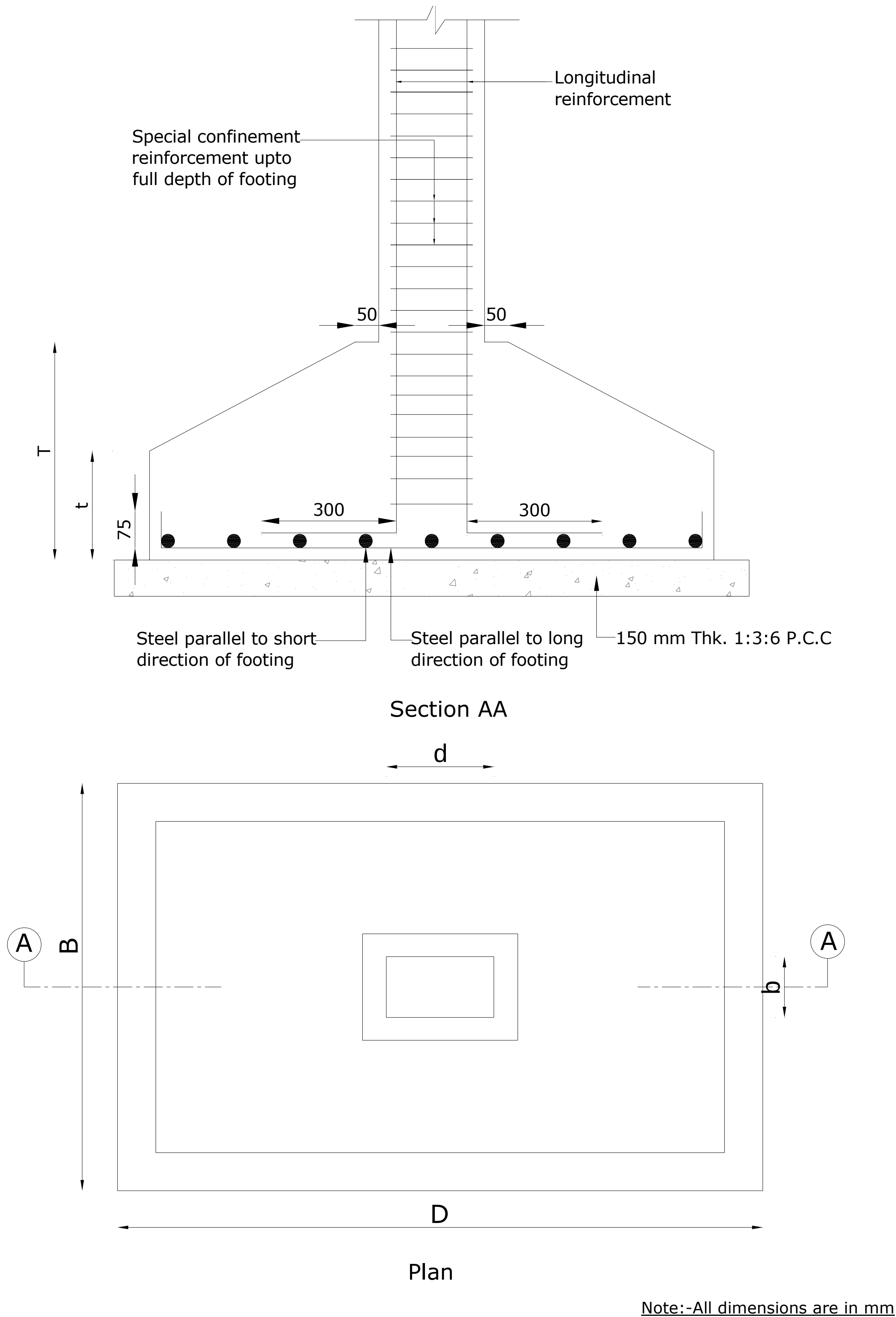


Figure 4.16 Typical detail of R.C.C footing

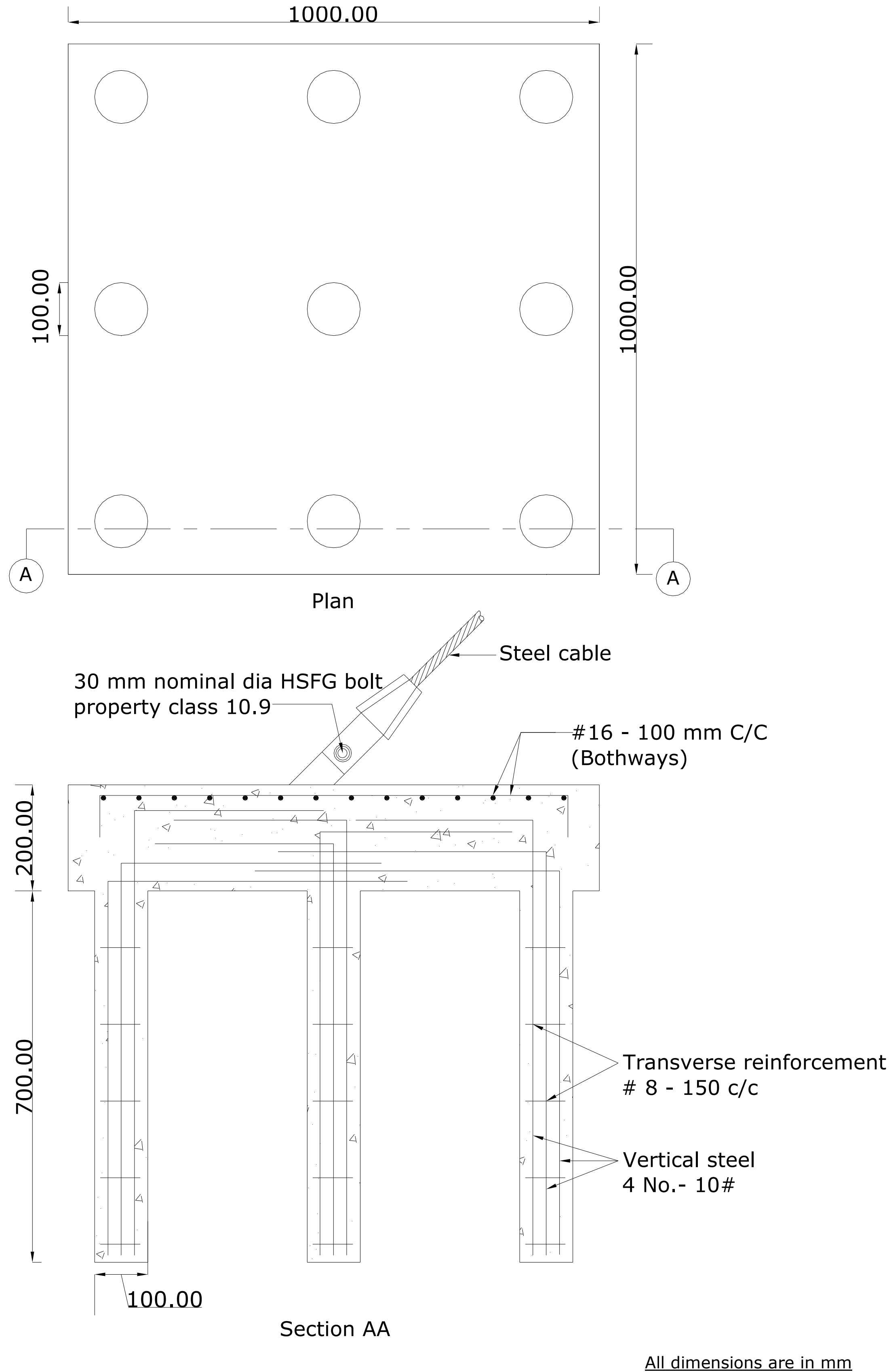


Figure 4.17 Typical detail of anchorage of cable

4.8 SUMMARY

After performing cable analysis, it is observed that cable carry loads through axial stresses, which utilizes entire cable's cross section. As well as single layer cable system is impracticable for relatively long span due to its fluttering effect during wind loading. In case of double layer cable, due to the connectivity of two cables using strut, less diameter of cable also gives permissible horizontal and vertical deflection. In design of strut, Slenderness ratio is too high so use of bigger section is necessary to avoid buckling of the member though compressive forces are very less. A special type of hinge connection has been developed at top of column to release moment. High amount of horizontal and vertical uplift force is present at the bottom of the anchor. An anchorage of cable is designed using the combination of gravity + ground anchor system.

5. DOUBLE LAYER GRID AND BRACED BARREL VAULT STRUCTURES (SPACE TRUSS)

5.1 GENERAL

A growing interest is expressed now-a-days by architects and engineers in shapes and forms which skeletal space systems are able to provide. They appreciate the visual beauty and the impressive simplicity of lines in modern space structures and there is a noticeable trend towards leaving the structural grid members exposed as part of the architectural expression. [3]

The term space structure refers to a structural system that involves three dimensions. In case of a space structure, combination of the configuration, external loads, internal forces and displacements of the structure extends beyond a single plane.

Steel skeletal space trusses are three-dimensional structures capable to cover large column free span. These structures constructed from either individual elements or prefabricated modules possess a high strength-to-weight ratio and stiffness. [3]

A grid is a structural system involving one or more planar layers of elements. A single layer grid or flat grid consists of a planar arrangement of rigidly connected beam elements. The external loading system for a flat grid consists of forces perpendicular to the plane of the grid and/or moments whose axes lie in the plane of the grid. The reason for classification of a flat grid as a space structure is that its external loads and displacements do not lie in the plane that contains its (idealized) configuration.

A double layer grid consists of two parallel layers of elements forming top and bottom layers that are interconnected together with vertical and diagonal members. In double layer grids the top and bottom grids are identical, with the top layer positioned directly over the bottom layer. Double layer space grids are usually formed from pyramidal units with triangular or square bases resulting into either identical parallel top and bottom grids offset horizontally to each other or parallel top and bottom grids each with a different configuration interconnected at the node points by inclined web members to form a regular stable structure. Elements of double layer grid allow for greater structural depth to accommodate longer spans.

Braced barrel vaults appear as an evolution of arches. A barrel vault is obtained by arching a grid along one direction. The result is a cylindrical form that may involve one, two or more layers of elements. The use of metal has enabled construction to be carried out with factory prefabricated elements which may be assembled on site. Maximum efficiency may be attained for shapes with rectangular surfaces and a length/width ratio between 1 and 2. The optimum shape (rise/span ratio) is in the region of 0.15 to 0.20 (Fig. 5.1).

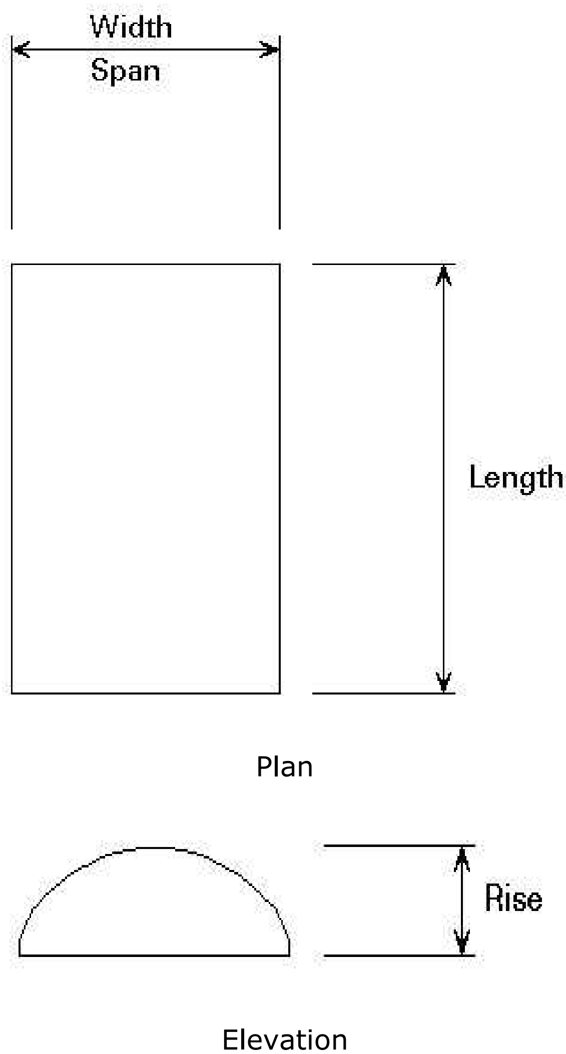


Figure 5.1 Braced barrel vault

Several layer geometries are possible. In practice, three directional systems offer the most advantages. They may usually be analyzed by assuming pin-jointed behavior for the nodes. This assumption does not hold, however, for some systems where bending rigidity must be taken into account, e.g. for a vault composed of prefabricated elements rigidly joined by high strength bolts. The sensitivity of these systems to asymmetrical actions, in particular to wind, should not be underestimated. Such actions can even bring about force reversal in the members, which is an additional reason for choosing a three directional geometry in which the length of all elements is identical.

In designing a grid configuration the suitability of a pattern for each particular case should be considered with regard to the shape and size of the boundary, support positions, loading characteristics, materials to be used and the manner in which the structure is to be constructed.

Steel space trusses may be used efficiently to form roofs, walls and floors for projects such as shopping arcades, sports stadia, exhibition halls, aircraft hangers and similar major structures. Double layer grid is also used for multi-storey buildings.

5.2 CLASSIFICATION OF GRID SYSTEM

Space trusses are classifies as single, double or multilayered structures which may be flat resulting in grid structures or may be curved in one or two directions, forming barrel vaults. Grid structures can be further categorized into lattice and space grids in which the members may run in two, three or four principal directions.

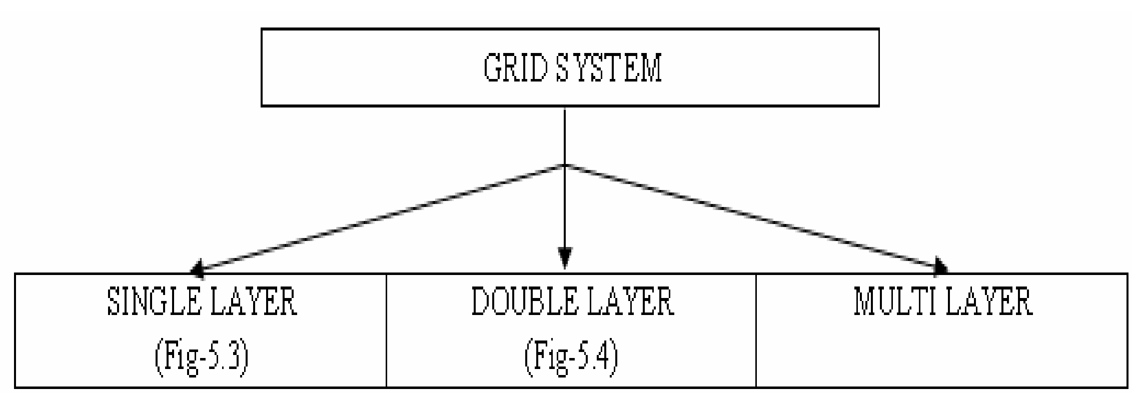
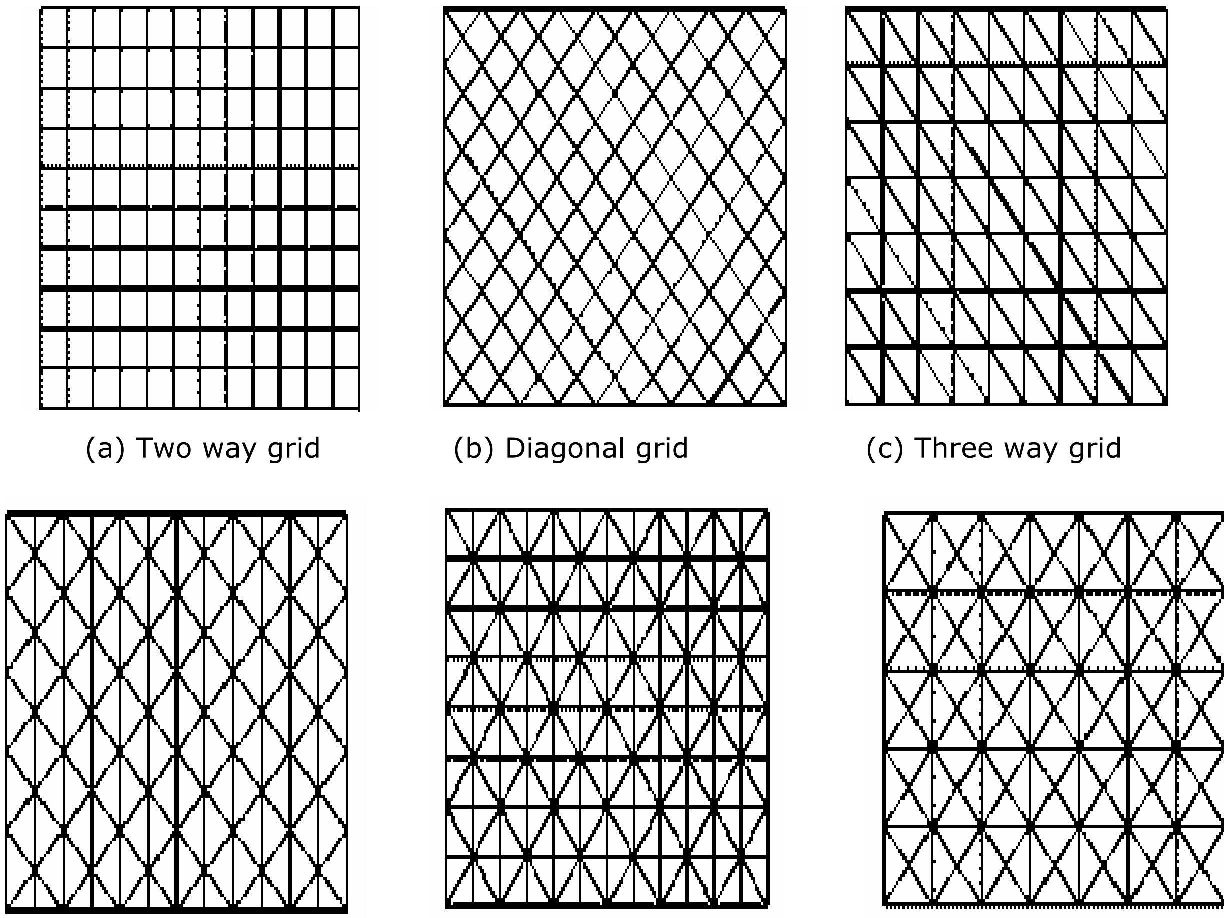


Figure 5.2 Classification of grid system



(a) Two way grid (b) Diagonal grid (c) Three way grid

(d) Three way grid (e) Four way grid (f) Four way grid

Figure 5.3 Different types of single layer grid

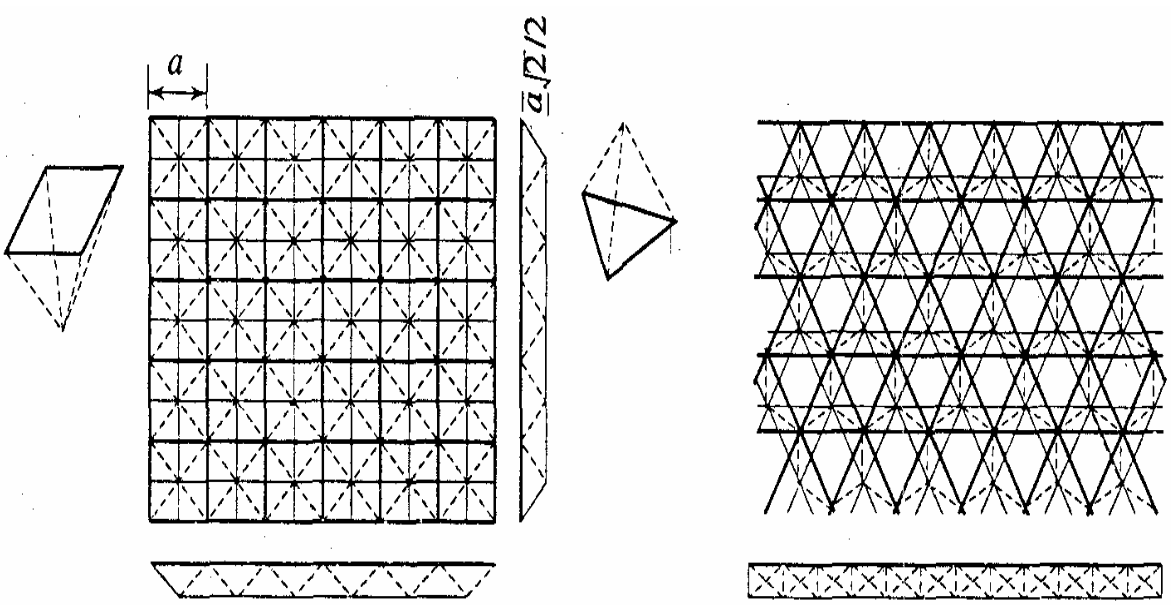


Figure 5.4 Double layer grids

5.3 DOUBLE LAYER GRID

5.3.1 Types

Several types of prefabricated double layer grids are available. Mero, oktaplatte, Unistrut, Space deck, Space grid, nenk, Nodus, Triodetic, Diamond truss, Unibat are some of the trade name. Views of some commonly used patterns of double layer grids are shown below in Figures. In all these figures, the top layer elements are shown by thick lines and the bottom layer elements as well as the web elements are shown by thin lines. The double layer grid of Fig. 5.5 consists of a two-way top layer and a two-way bottom layer set at 45^0 to the edges of the grid. This type of grid is suitable for exceptionally heavy loading and there are few supports near the corners. In the case of the grid of Fig. 5.6 both the top and bottom layers have a diagonal pattern. Due to the diagonal members' configuration top, bottom and inclined members are of identical size. There are also many double layer grids built with a two-way pattern for one of the layers and a diagonal pattern for the other layer. [3]

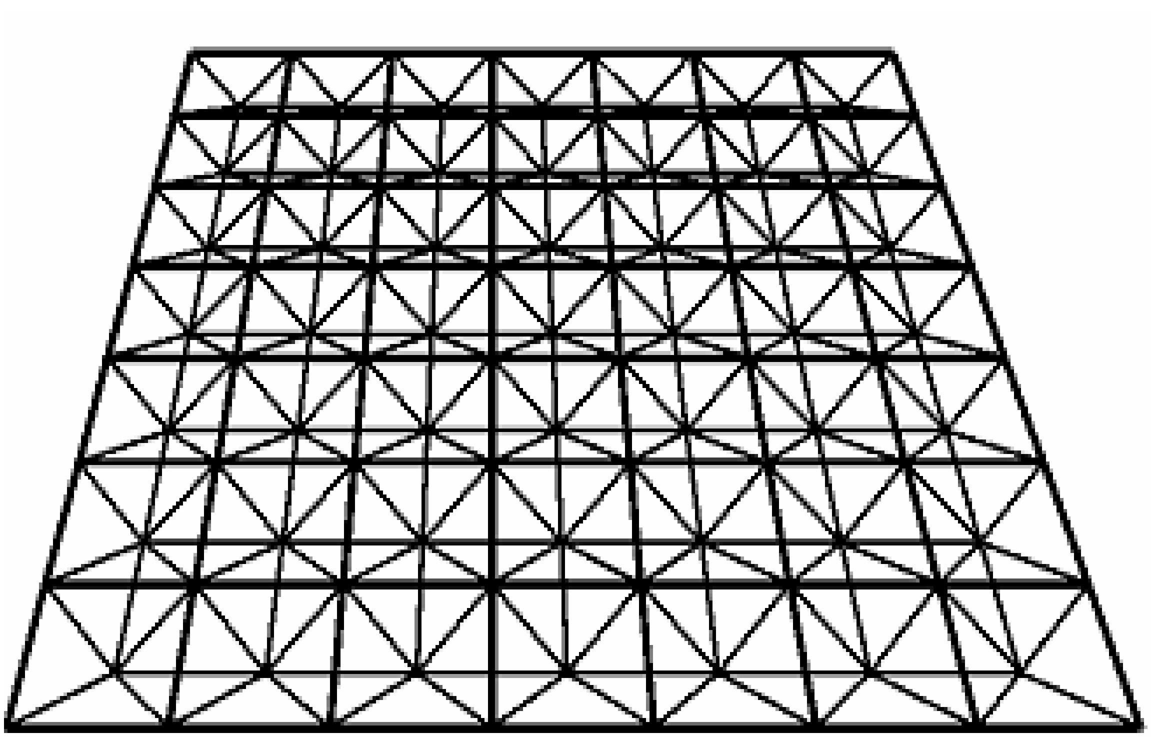


Figure 5.5 Two-way on two-way (square on square offset)

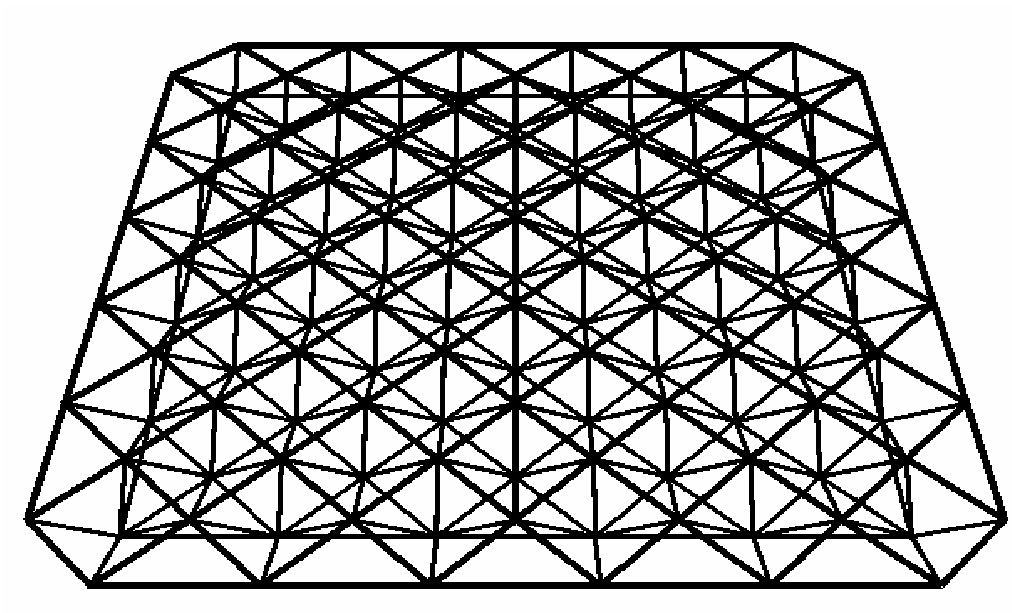


Figure 5.6 Diagonal on diagonal---double layer grid

A double layer grid of a different kind is shown in Fig. 5.7. The top and bottom layers are of an identical shape and are positioned such that their plan views are coincident. Also, in this case all the web elements lie in vertical planes. The result is a double layer grid that effectively consists of a number of intersecting plane trusses. A grid of this type is referred to as a 'truss grid'. A truss grid may be regarded as a flat grid whose elements are trusses.

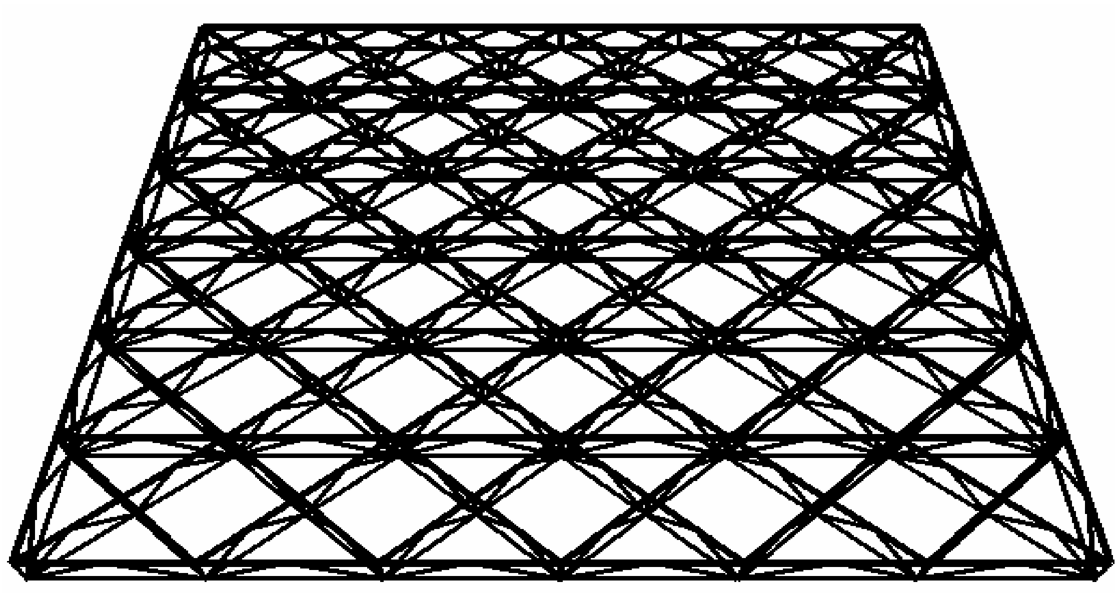


Figure 5.7 Three way truss grid---double layer grid

A primary double layer grid pattern, such as the one shown in Fig. 5.5, is often used as a basis for the creation of various reduced forms by removing a number of elements. An example of this is shown in Fig. 5.9. This grid is obtained from the grid of Fig. 5.5 by removing the bottom layer and web elements that are connected to a number of bottom layer nodes. A similar process is used for obtaining the reduced grid of Fig. 5.10 from the grid of Fig. 5.6. Also, the diagonal truss grid of Fig. 5.10 is obtained by removing the non-boundary third-direction trusses of the grid of Fig. 5.7.

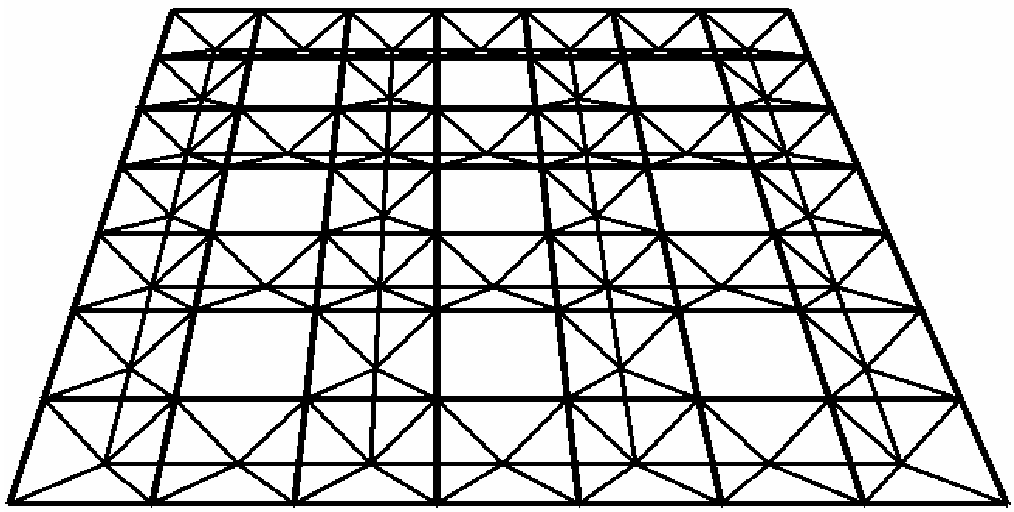


Figure 5.8 Reduced two way on two way ---double layer grid

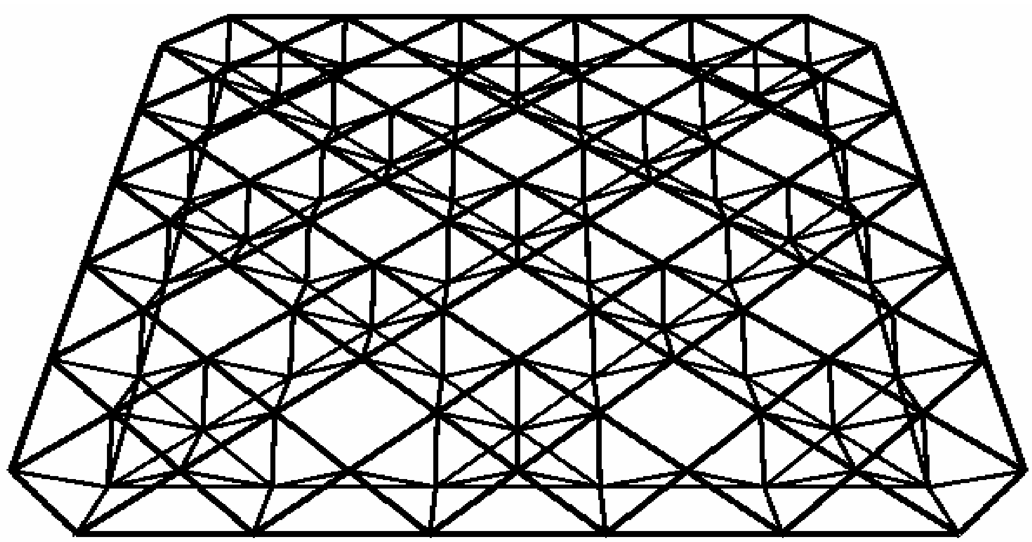


Figure 5.9- Reduced diagonal on diagonal ---double layer grid

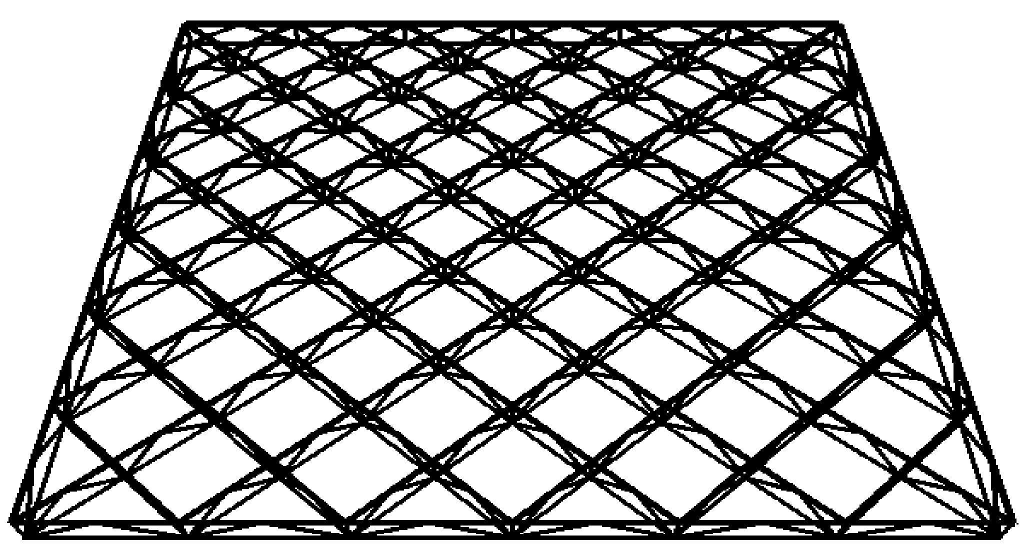


Figure 5.10 Diagonal trusses ---double layer grid

5.3.2 Supporting methods

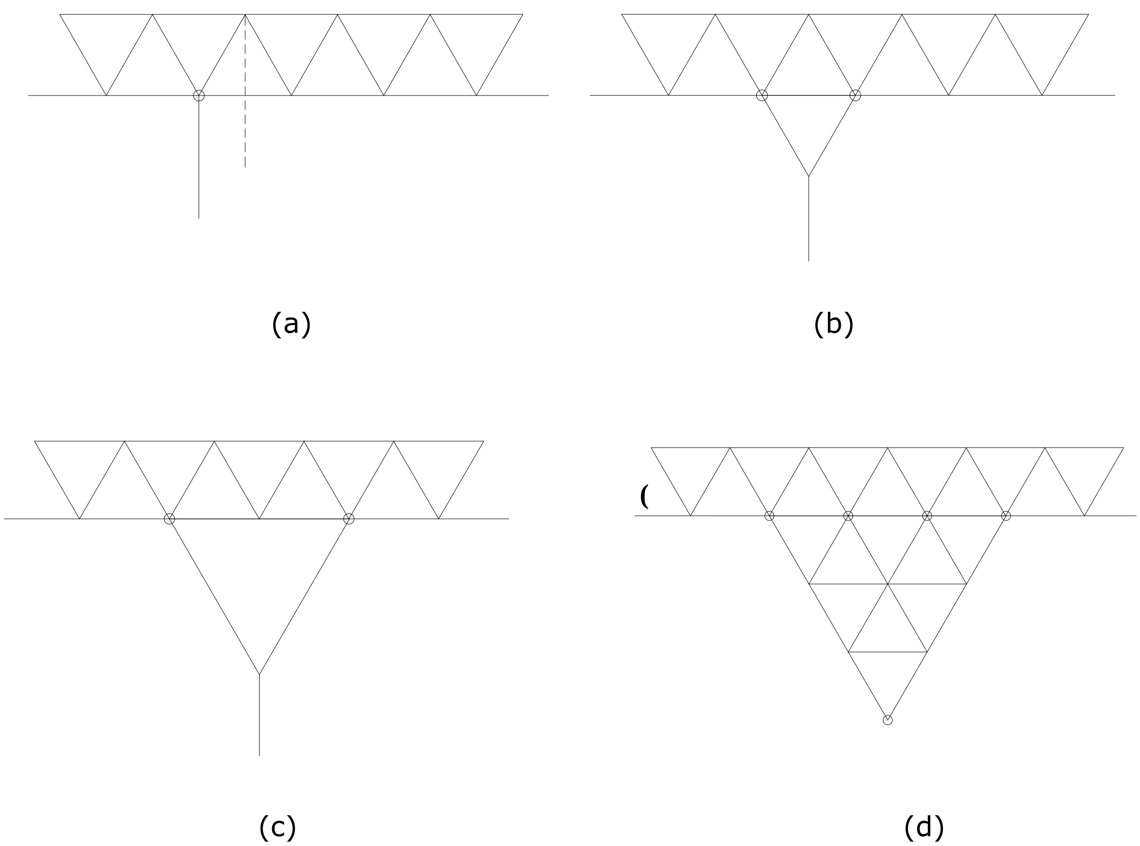
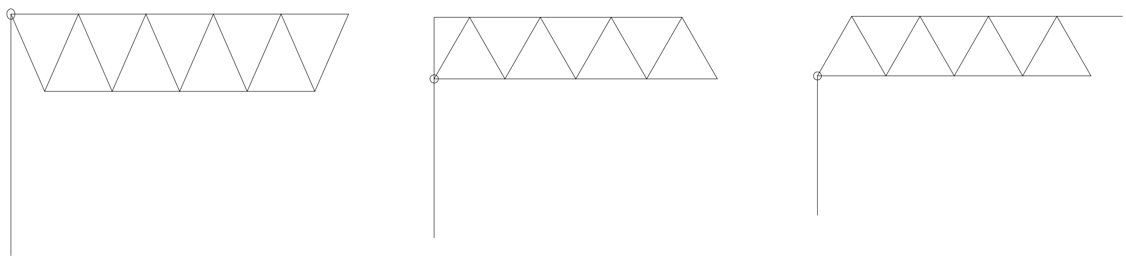


Figure 5.11- Different methods of supporting the grid

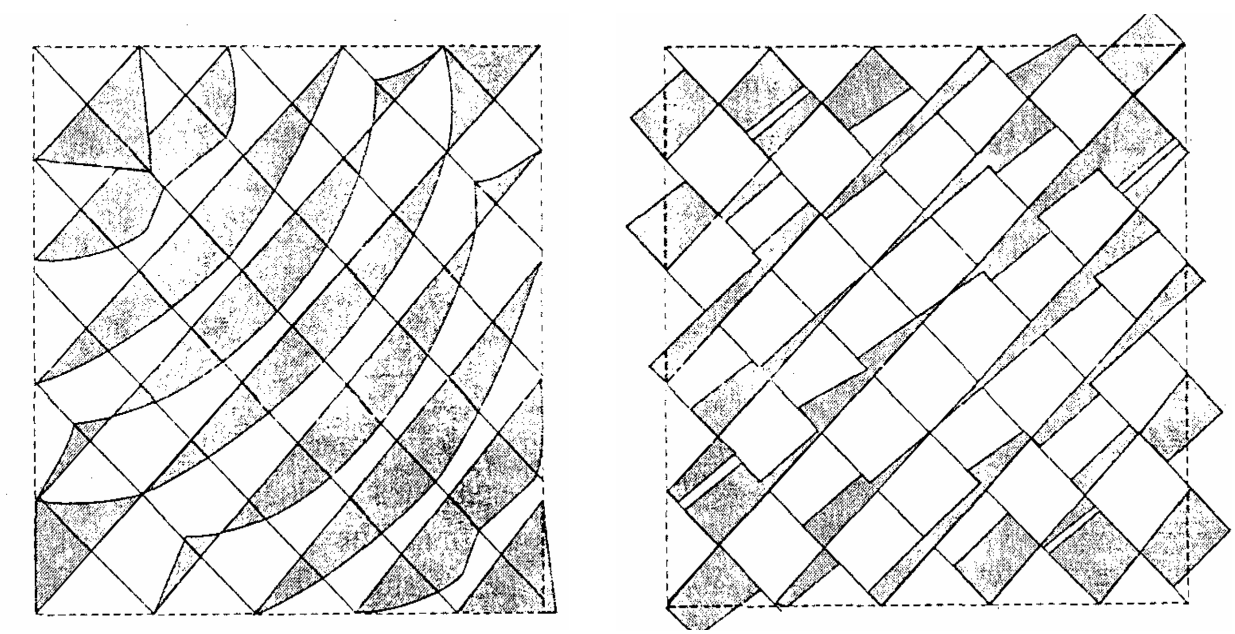


(a) Cornice (b) Vertical (c) Mansard

Figure 5.12 Different types of grid edge profile

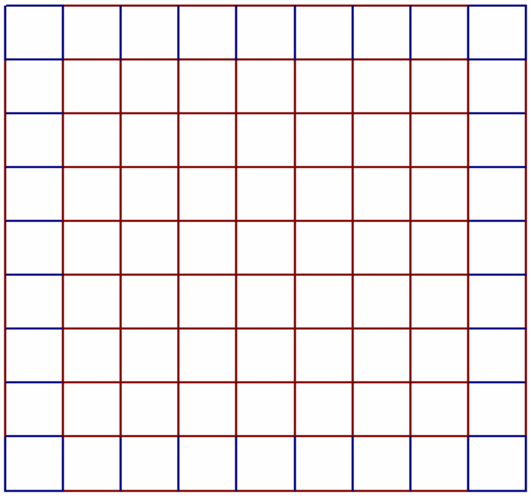
5.3.3 Structural behavior

There is a fundamental difference between the structural behavior of single layer grids and that of double layer grids. Flat grids are 'bending dominated' with the elements being under bending moments, shear forces and torque. In contrast, the main internal forces in the elements of double layer grids are axial forces. Top members always subjected to compression, bottom members tension and diagonal members either in compression or tension. [3]

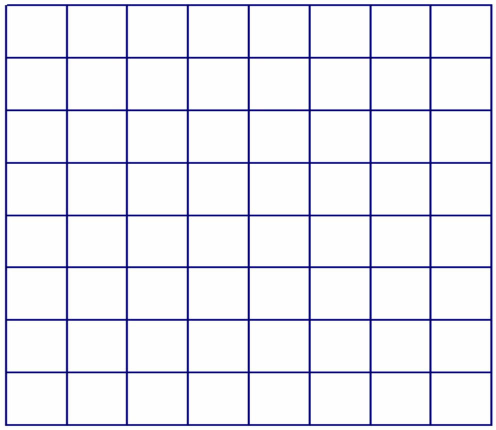


(A) Bending moment diagram (b) Shear force diagram

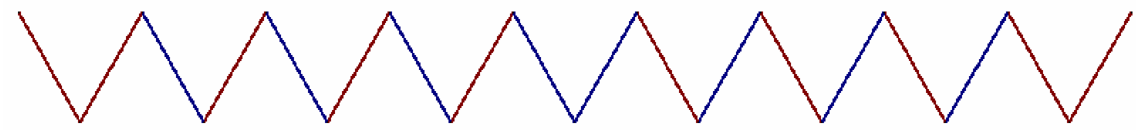
Figure 5.13 Internal force diagrams in single layer diagonal grid



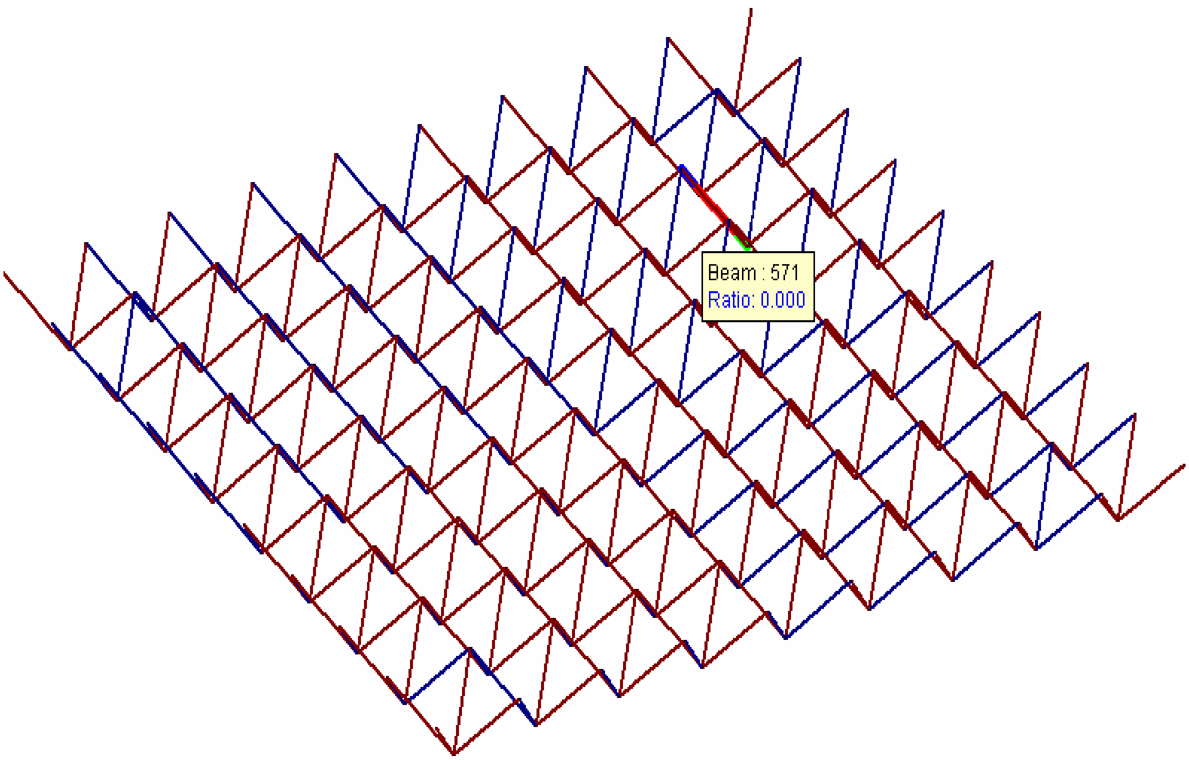
(a) Top layer



(b) Bottom layer



(c) Elevation of diagonal member



(d) 3d view of diagonal member

Figure 5.14 Internal force diagrams in double layer grid

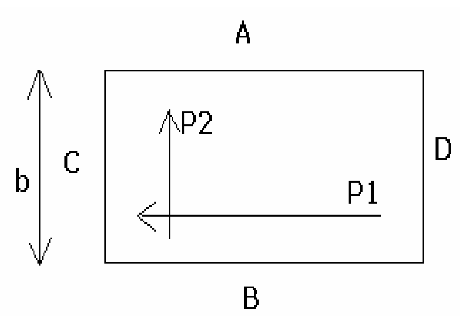
5.4 APPROXIMATE ANALYSIS OF DOUBLE LAYER GRID

For the final Analysis and design of space trusses, the computer analysis is required. As such to get idea of accurate analysis, approximate analysis of structure is carried out. [3] Some of the important approximate analyses for double layer grids are:

5.4.1 Approximate formulae for chord forces and reactions

Applicable to only square on square offset and square on large square grids. Formulae can be used to determine the maximum axial loads in the top and bottom chord members in the center of the grid and the maximum midspan reaction along the sides.

Assumption: - this grid is assumed to be supported regularly around all four sides.



(I) Members parallel to sides A and B, maximum top and bottom chord forces

$$P1 = T * \frac{n}{D} * F1 \qquad \text{... (5.1)}$$

(II) Members parallel to sides C and D, maximum top and bottom chord forces

$$P2 = T * \frac{n}{D} * F2 \qquad \text{... (5.2)}$$

5.4.2 Girder analogy method

This method is most suitable for areas in which rectangularity ratio is more than two. However it gives appropriate results for length/width ratio one or more than one. It is not possible to estimate the diagonal member sizes.

5.4.3 Slab Analogies

Double layer grids may be replaced by an equivalent plate to obtain indirect solutions to the stress distribution in the real structures.

5.4.4 Simplified slab analogy method

This method is suitable for edge-supported space trusses with rectangularity ratios less than 2. It is assume that the truss consists of two separate structural systems in the x and y direction carrying portions of the total load W_x and W_y such that

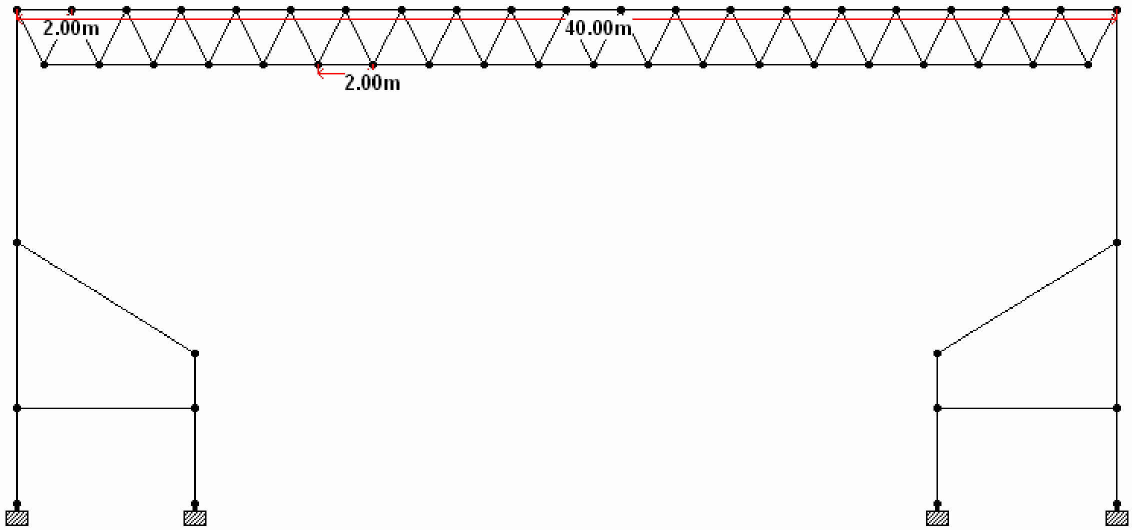
$$W_x + W_y = W_t \quad \text{... (5.3)}$$

This method becomes increasing inaccurate with rectangularity ratios approaching towards two.

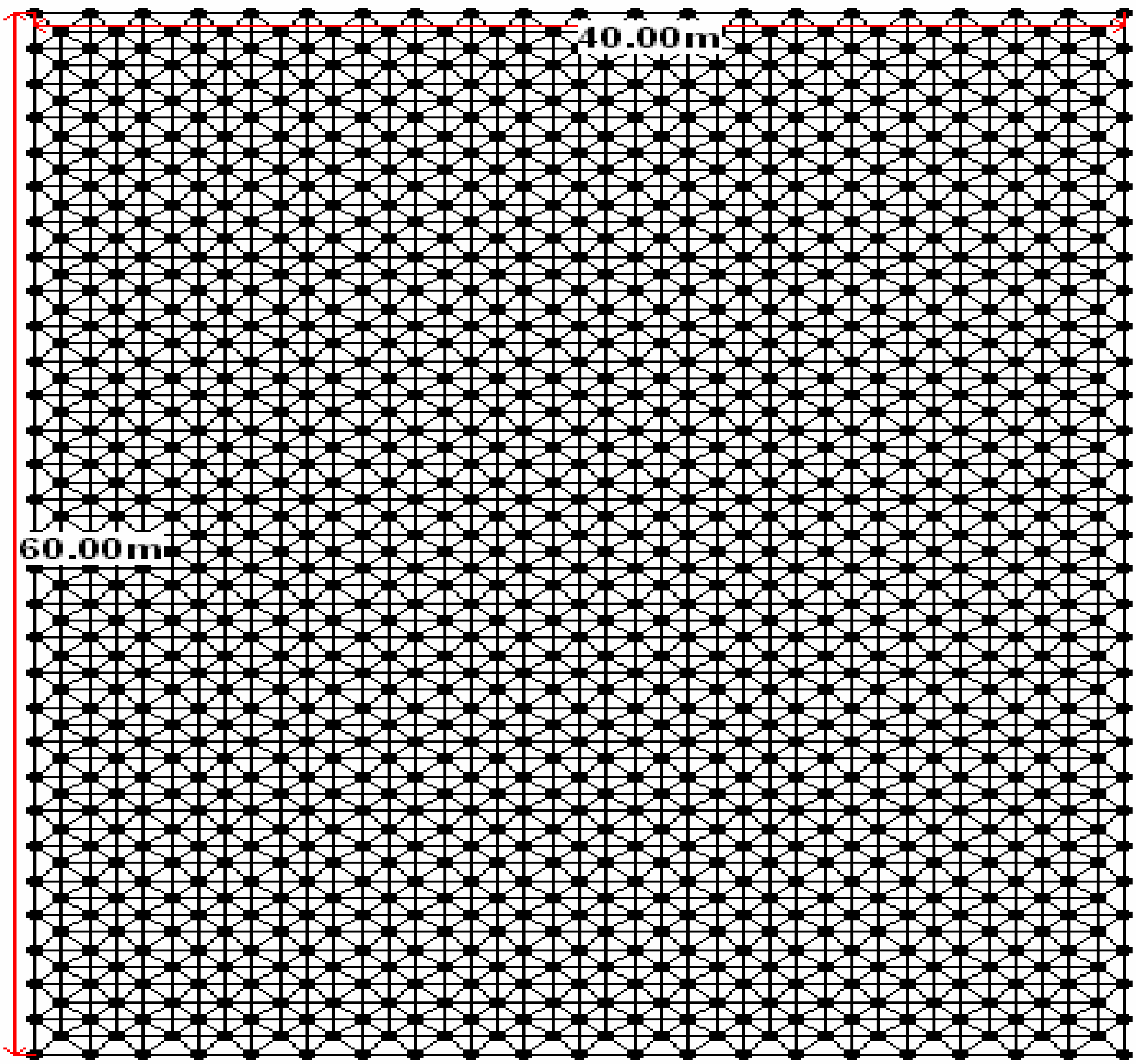
APPROXIMATE ANALYSIS OF DOUBLE LAYER GRID

DATA:

Size of stadium:	40 m X 60 m	
Width of structure:	40	m
Length of stadium:	60	m
No. of division along width direction:	20	No.
No. of division along length direction:	30	No.
Size of each member along width:	2	m
Size of each member along length:	2	m
Height:	2	m
Self weight of double layer grid:	0.25	kN/m^2
Weight of roofing + Fixtures:	0.15	kN/m^2
Total DL of double layer grid:	0.4	kN/m^2
Total LL of double layer grid:	0.75	kN/m^2
Total WL of double layer grid:	1.206	kN/m^2
Total load on double layer grid:	2.8272	kN/m^2



Elevation



Plan

1) Approximate formulae for chord members and reactions : [3]

As such here the rectangularity ratio (grid side ratio) is : 1.5

F_1= 0.04 [3]

F_2= 0.08

Maximum top and bottom chord forces:

$P_1 = T \; X \; n \; X \; F_1 / D$ & $P_2 = T \; X \; n \; X \; F_2 / D$

T= Total load

T= 2.8272*40*60

T=	6785.28	kN
n=	2	m
D=	2	m
F_1=	0.04	
F_2=	0.08	
P_1=	271.411	kN
P_2=	542.822	kN

Reactions:

$R = 8T \; X \; n \; X \; F_2 / a$ … (5.4)

R= 217.129 kN

2) The Simplified Slab Analogy Method : [3]

ά= 1.5

$$Wx = \frac{a^4}{a^4 + 1} Wt \qquad Wy = \frac{1}{a^4 + 1} Wt \qquad \text{...(5.5)}$$

Wx=	2.36086	kN/m^2	*Wy*=	0.46634	kN/m^2
Mx =	Wx*L*L/8		*My*=	Wy*L*L/8	
	472.172	kNm		209.854	kNm
Fx=Tx=	Mx/D		*Fy=T*	My/D	
	236.086	kN	*y*=	104.927	kN

3) The Slab Analogy Method : [3]

$$M\max = \frac{8 * q * a1 * a^2}{\Pi^4} \qquad \text{...(5.6)}$$

M_{max}= 744.523

Maximum Axial forces in top and bottom layers are:

F_{max}= M_{max} /D kN

372.261

Maximum shear force is:

$$Q\max = \frac{8 * q * a1 * a}{\Pi^3} \quad ...(5.7)$$

Q_{max}= 58.445 kN

4) The Girder Analogy Method : [3]

Line load= 2.8272*40

113.088 kN/m

Moment: W*L*L/8

22617.6 kNm

Internal forces in chord members at mid span: Moment / Truss depth

11308.8 kN

Truss has 20 top members and 19 bottom members.

Force in top members: 565.44 kN

Force in bottom members: 595.20 kN

Comparison Between All Methods:

Table 5.1 Comparison of approximate methods

Name of method	Member Designation			
			% Difference to exact analysis	
	Top Member	Bottom Member	Top member	Bottom member
1) Approximate Formulae For Chord Members And Reactions	542.82	542.82	3.98	10.05
2) The Simplified Slab Analogy Method	236.09 & 104.93	236.09 & 104.93	----	----
3) The Slab Analogy Method	372.26	372.26	51.62	60.47
4) The Girder Analogy Method	565.44	595.20	-0.18	0.37
5) Computer Analysis	564.44	597.38		

5.5 BRACED BARREL VAULTS

5.5.1 Types

Some examples of barrel vault configurations are shown below in figures. Fig. 5.15 shows a single layer barrel vault that is obtained by arching a diagonal flat grid. A barrel vault with a diagonal pattern is often referred to as a 'lamella barrel vault'. [7]

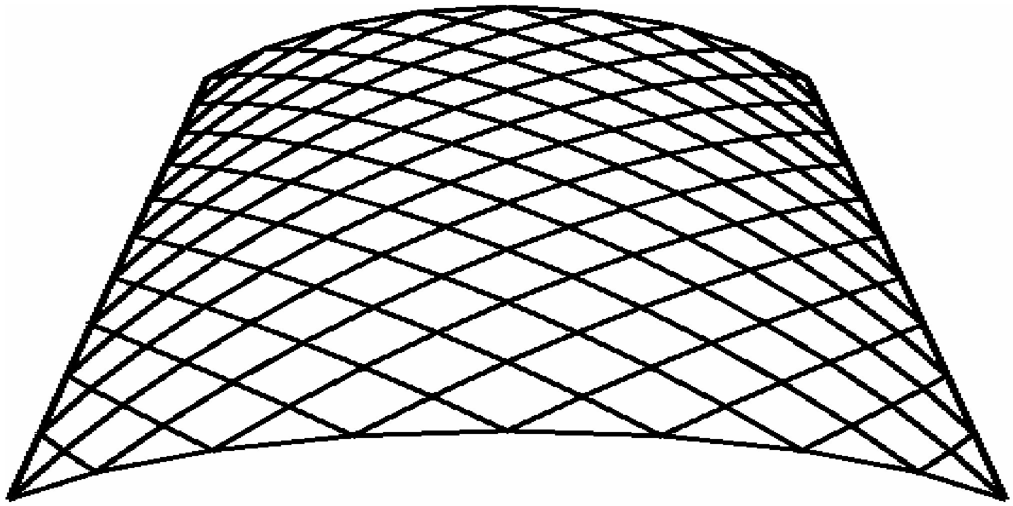


Figure 5.15 Lamella (diagonal) barrel vault

The barrel vault in Fig. 5.16 is similar to the one in Fig. 5.15 but has a three-way pattern.

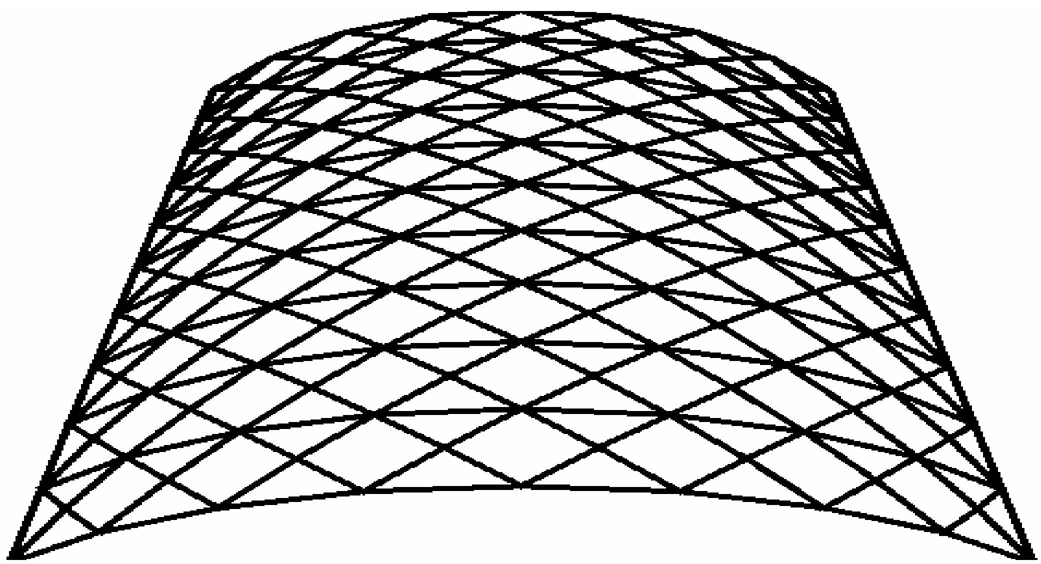


Figure 5.16 Three way barrel vault

A double layer barrel vault is shown in Fig. 5.17 with both the top and bottom layers having a two-way pattern.

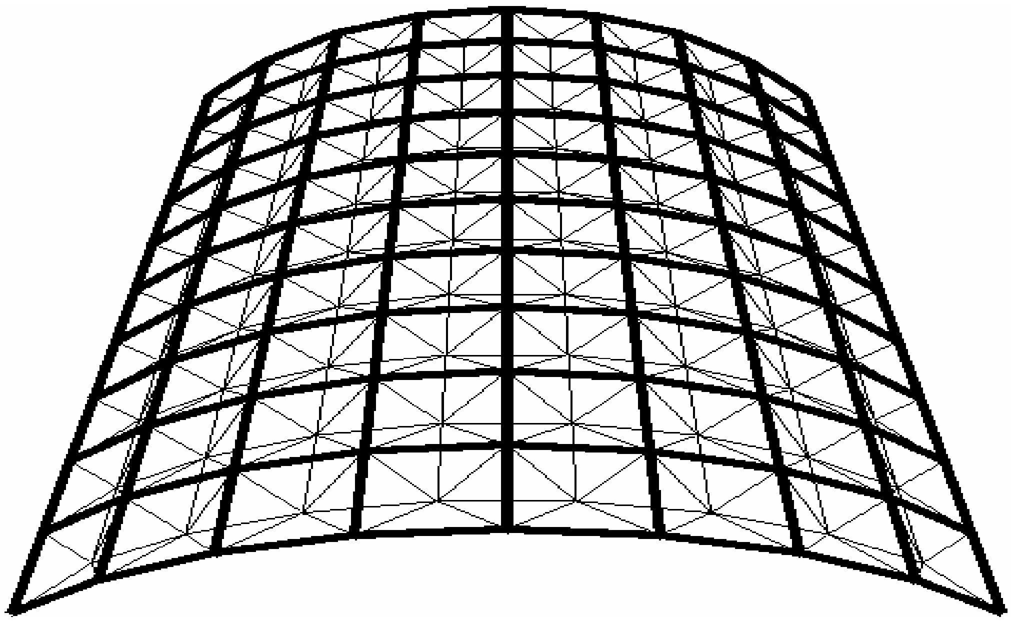


Figure 5.17 Two way on two way double layer barrel vault

Also, the barrel vault of Fig. 5.18 has a top layer and a bottom layer with interconnecting web elements. However, in this case the disposition of the elements results in a truss barrel vault that is a barrel vault that consists of intersecting curved trusses

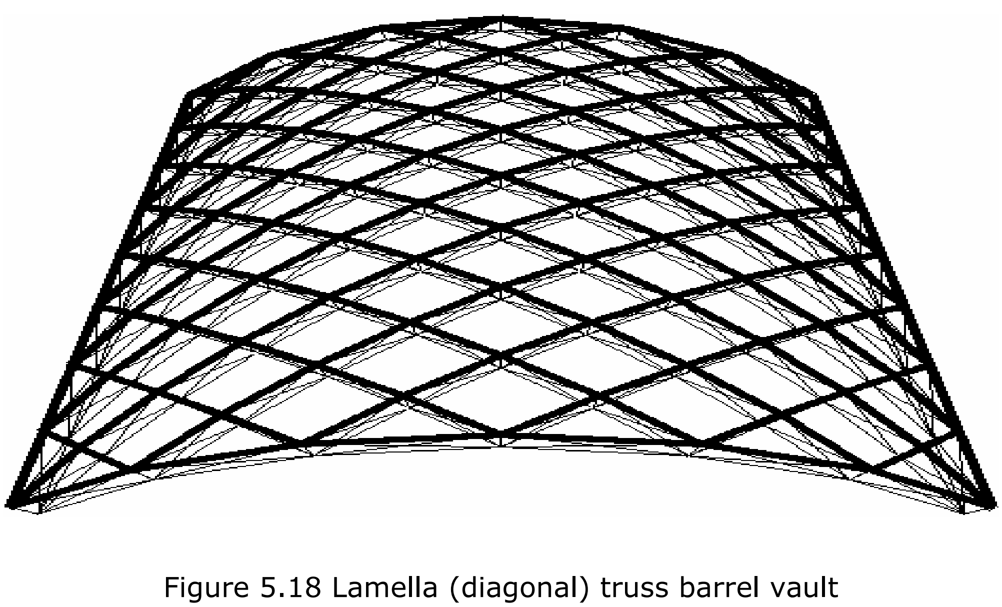


Figure 5.18 Lamella (diagonal) truss barrel vault

The shape of the cross-section of a barrel vault may vary along its longitudinal axis. Examples of this are shown in Figs 5.19 and 5.20. The surface of the lamella barrel vault of Fig. 5.19 is a part of a hyperboloid of revolution while the surface of the barrel vault of Fig. 5.20 is a part of an ellipsoid of revolution.

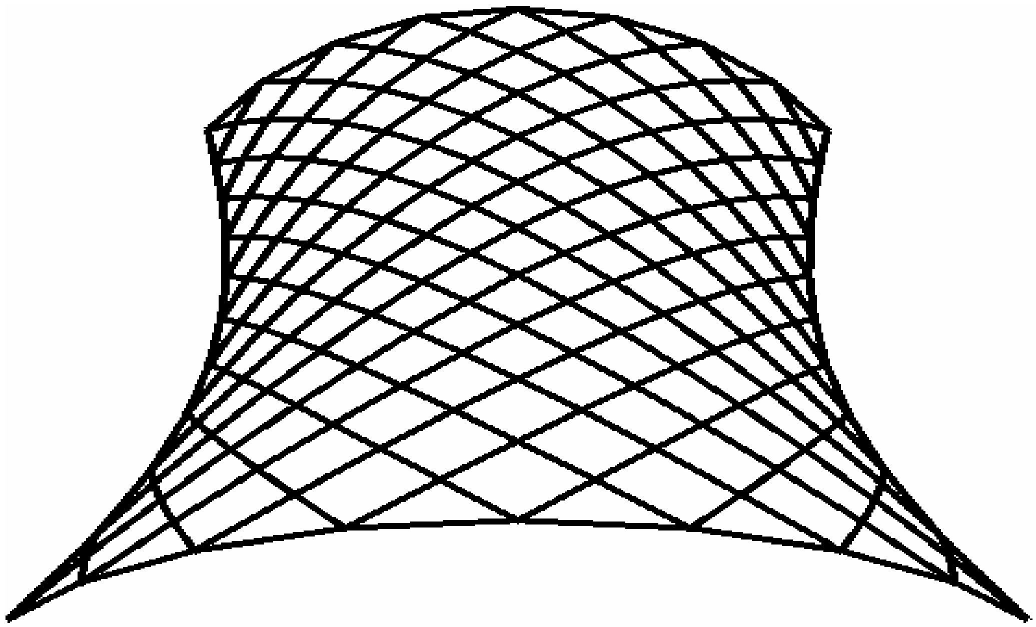


Figure 5.19 Hyperboloid lamella barrel vault

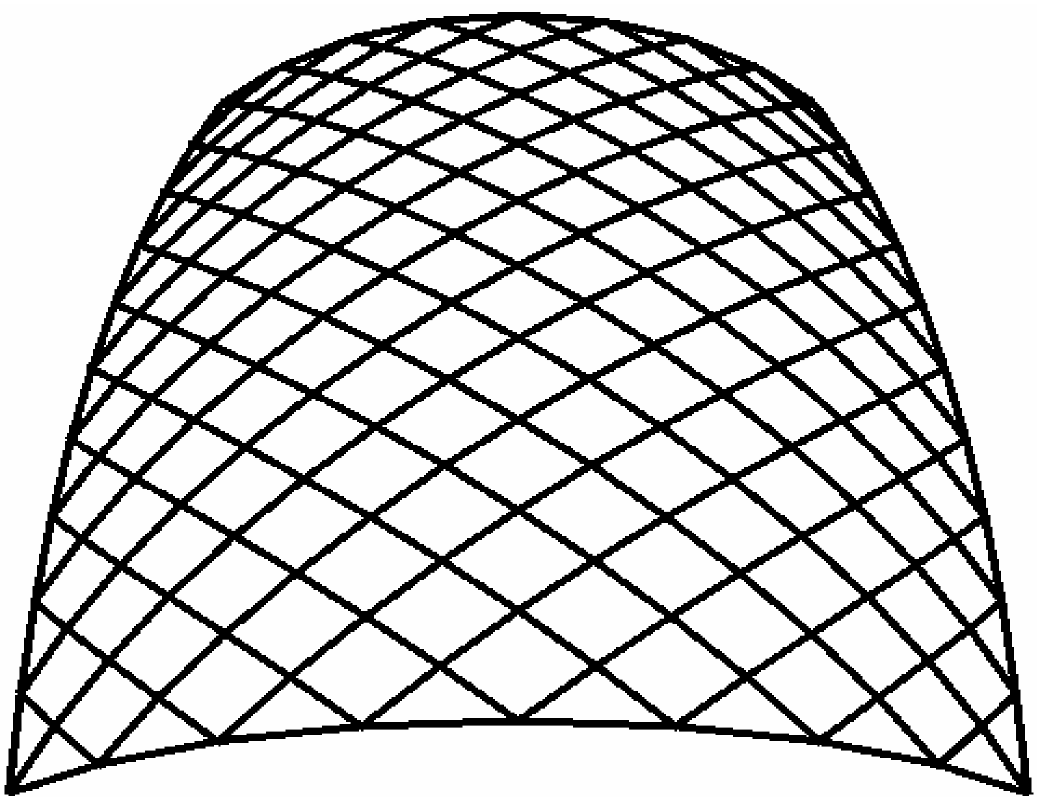


Figure 5.20 Ellipsoidal lamella barrel vault

An example of a 'compound barrel vault' is shown in Fig. 5.21. It is a typical type of braced barrel vault that consist of more than two braced barrel vaults. So a compound barrel vault is defined as a barrel vault that consists of two or more barrel vaults connected together along their sides. The compound barrel vault of Fig. 5.21 is obtained by combining three barrel vaults identical to the one in Fig. 5.16. Compound barrel vault is not effectively used for covering column free area.

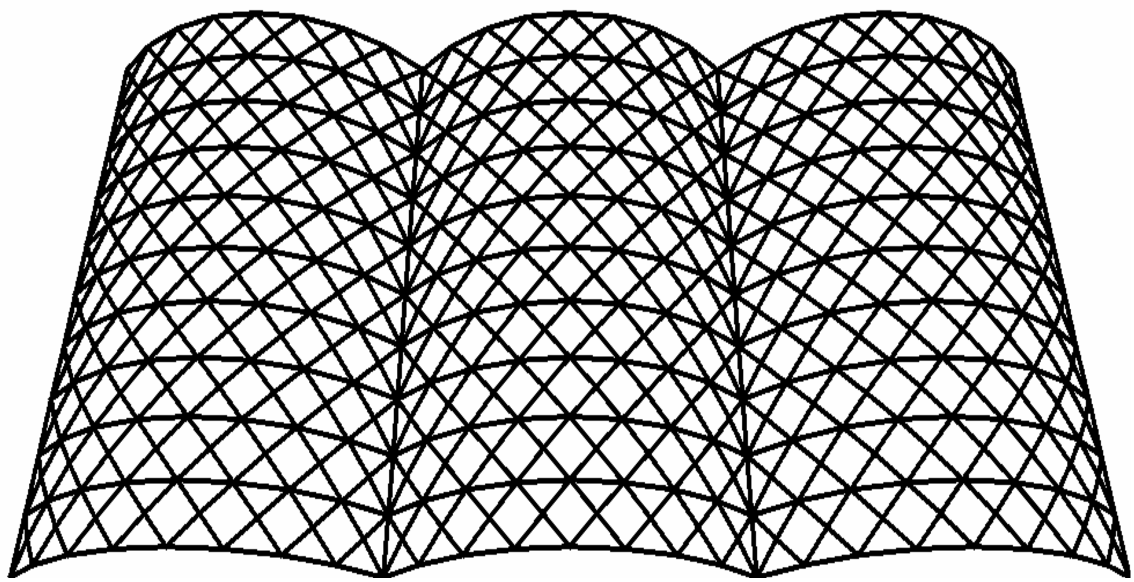


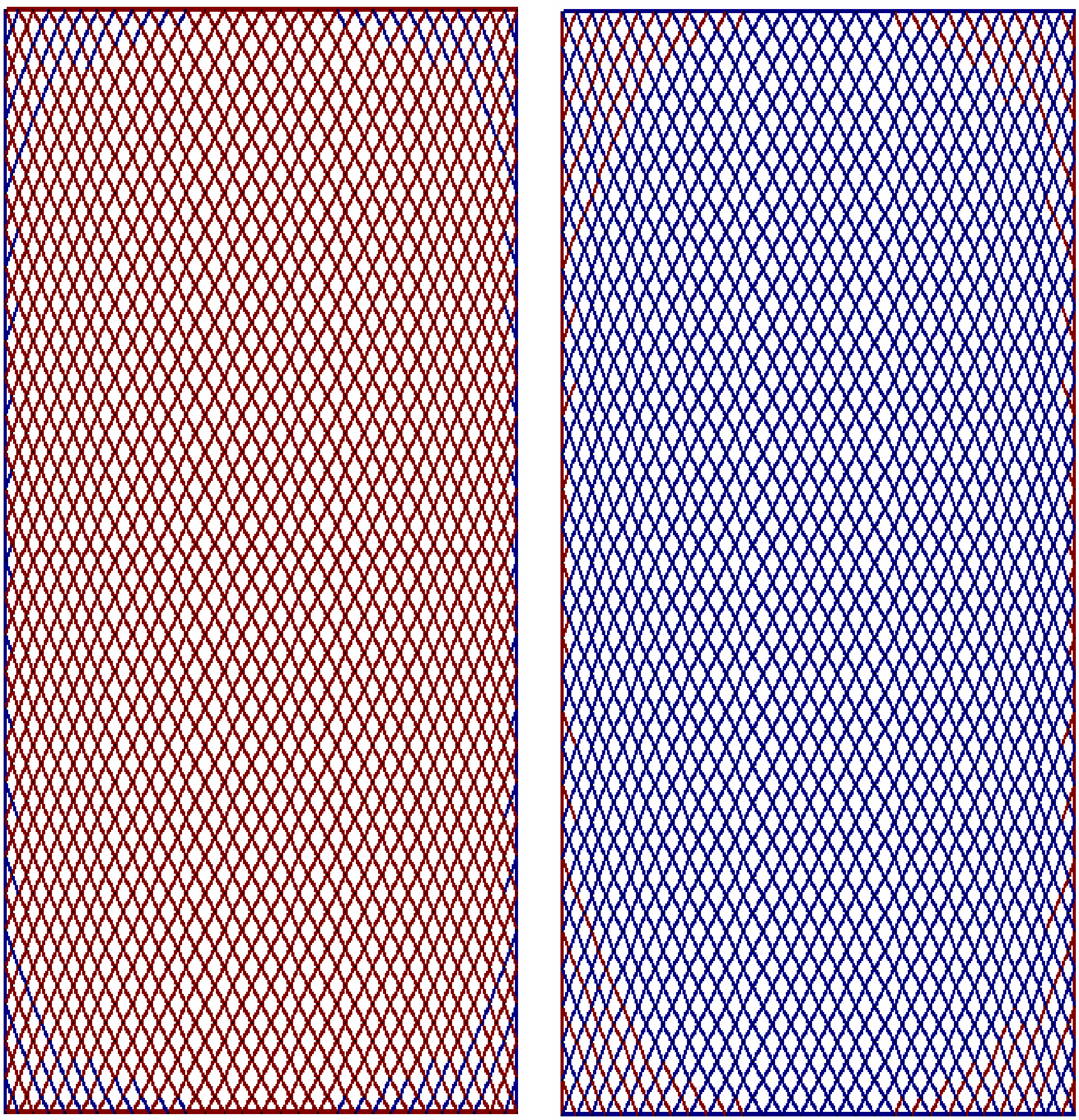
Figure 5.21-Compound three way barrel vault

The cross-sections of the barrel vaults in above figures are circular. However, a barrel vault may have a cross-section which has an elliptic, a parabolic or many other shapes.

Braced barrel vault are also classified on the basis of number of layers i.e. single or double layer, bracing of the system i.e. horizontal, vertical or inclined, supporting of the system i.e. at the corners, away from the corners, Based on different types of grid edge profiles like cornice, vertical, mansard etc. Braced barrel vault

5.5.2 Structural behavior

Braced barrel vault's structural behavior is same as that of the double layer grid. The main internal forces in the elements of braced barrel vault are axial forces. All members subjected to compression or tension depending on loading conditions. During vertical loading situation all top members are subjected to axial compression and side members along the length direction are subjected to axial tension as shown in figure 5.22 (A). When lateral loading is applied on the structure, all top members are subjected to axial tension while side members are subjected to axial compression i.e. reversal of stresses occur in the members shown in figure 5.22 (B).



(a) (b)

Figure 5.22 Internal force diagram of braced barrel vault

5.6 CONNECTORS

5.6.1 Types

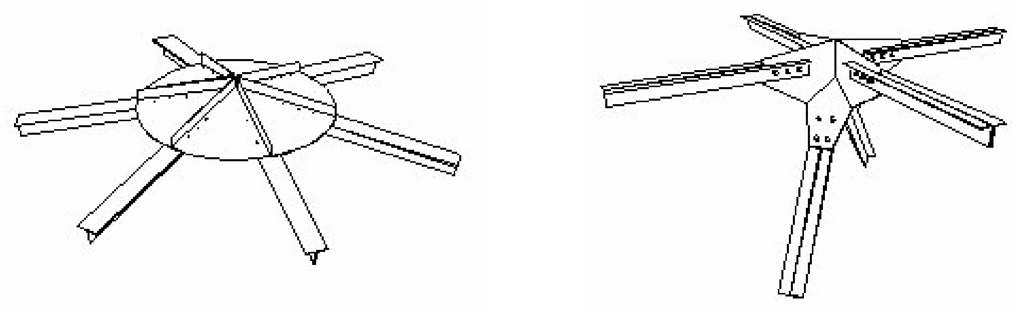
The most critical components of any space structure are the joints where the main structural members interconnect. The connector which is used at these joints is thus the most important part of any prefabricated system and the final commercial success relies on its effectiveness and simplicity. The connectors occupy 10-25% of the total amount of steel required for space frames. The node is a critical element when evaluating the cost of space structures. One node for 2.5-3.0 m^2 would seem to be an economical solution. Hence the selection of joint is important and may influence the economy of space frames. [3]

Several parameters govern the design of nodes. Nodes can be connected mainly by welding, bolting or by special fabrication. Except where pretensioned bolts are used, bolted connections reduce the resistance of net-sections. One of the determining factors in the choice of nodes is the number of members to be assembled. Apart from structural influences on the node itself, this problem is linked to the way the members are connected to the node and to considerations of space and ease of installation. The regularity of geometry resulting from the node determines the entire geometry of the structure.

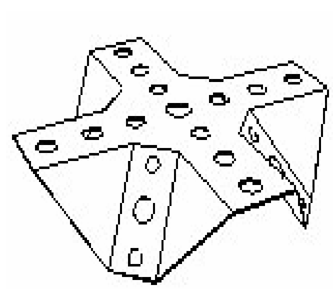
Different types of nodes are used in construction of space truss are shown in figure 5.23. Plated and folded nodes are usually connected to the member ends by means of bolted connections. For spatial types of structures special working nodes i.e. Mero node is used. Extruded nodes generally used for aluminum structures. Cast node is a typical type of node which is fabricated at site and system made from it is known as "Nodus" system. [10]

The node-to-member joining system determines how the ends of the members treated. Different treatment of member ends is shown in figure 5.24. For steel tubes generally special working and branch pipe cutting is used. While in case of angle sections generally straight cutting is used.

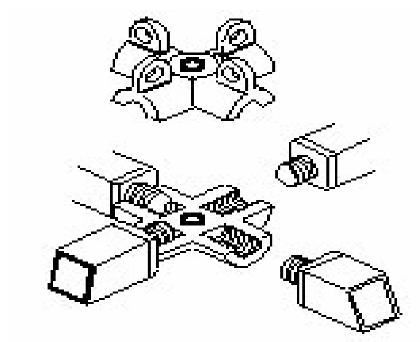
Most common used connectors systems are Mero, Nodus, Catrus, KE truss, Unibat, Unistrut, Space deck, SS truss etc.



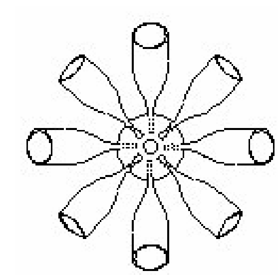
(a) Plate nodes



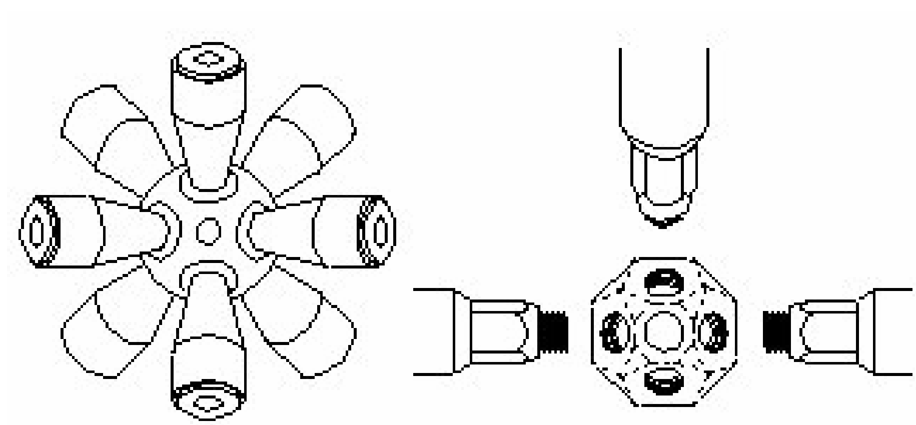
(b) Folded nodes



(c) Cast nodes

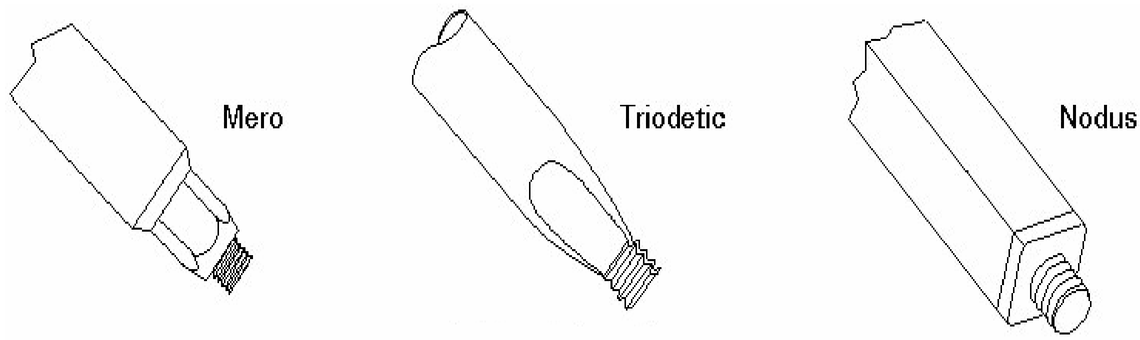


(d) Extruded nodes

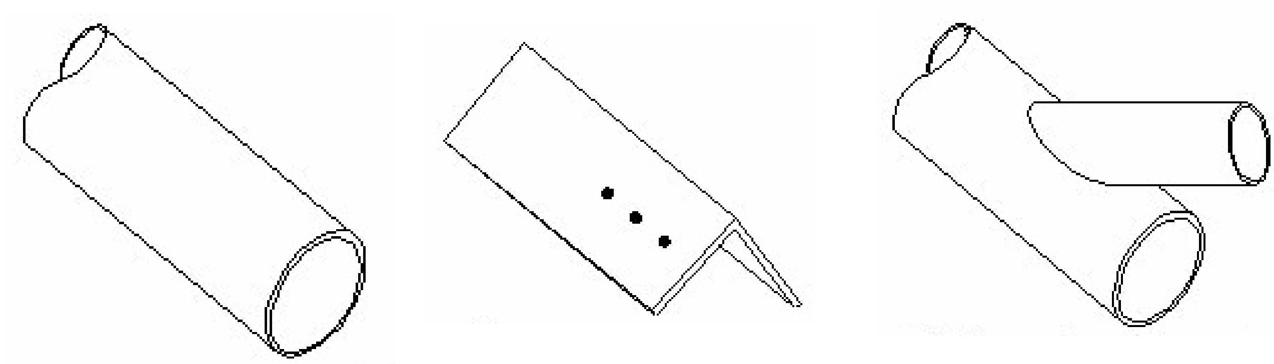


(e) Special working

Figure 5.23 Different types of nodes

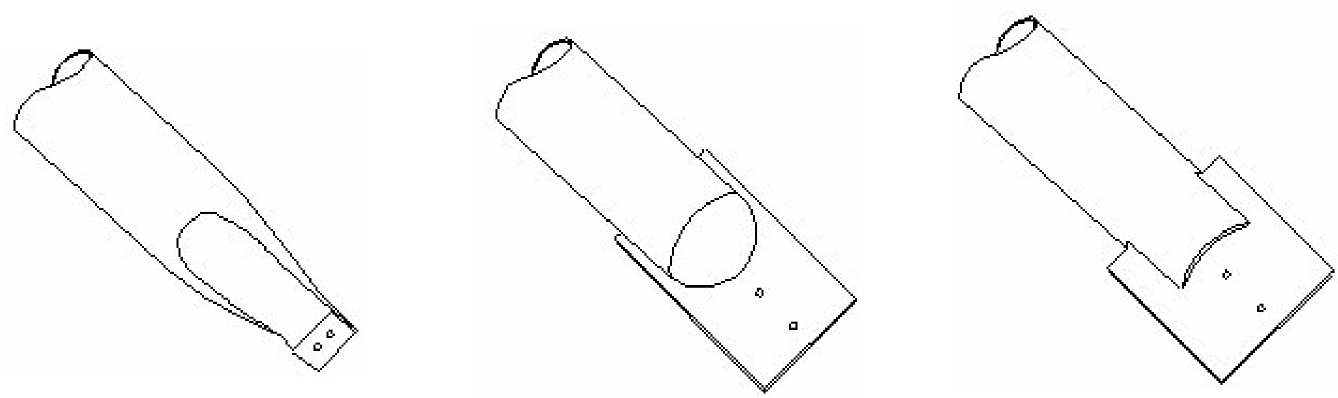


(a) Special working



(b) Straight cutting

(c) Branch pipe cutting



(d) Flattening

(e) Plate welding

Figure 5.24 Different treatment of member ends

5.6.2 The Mero System

The German Mero system (the name MERO stands for MEngeringhausen-ROhrbauweise, i.e. MEngeringhausen's Tubular construction) came on the market in 1943. Developed by Dr Ing. MEngeringhausen, this was the first connector in the world to be used in industrialized construction on the basis of mass produced components.

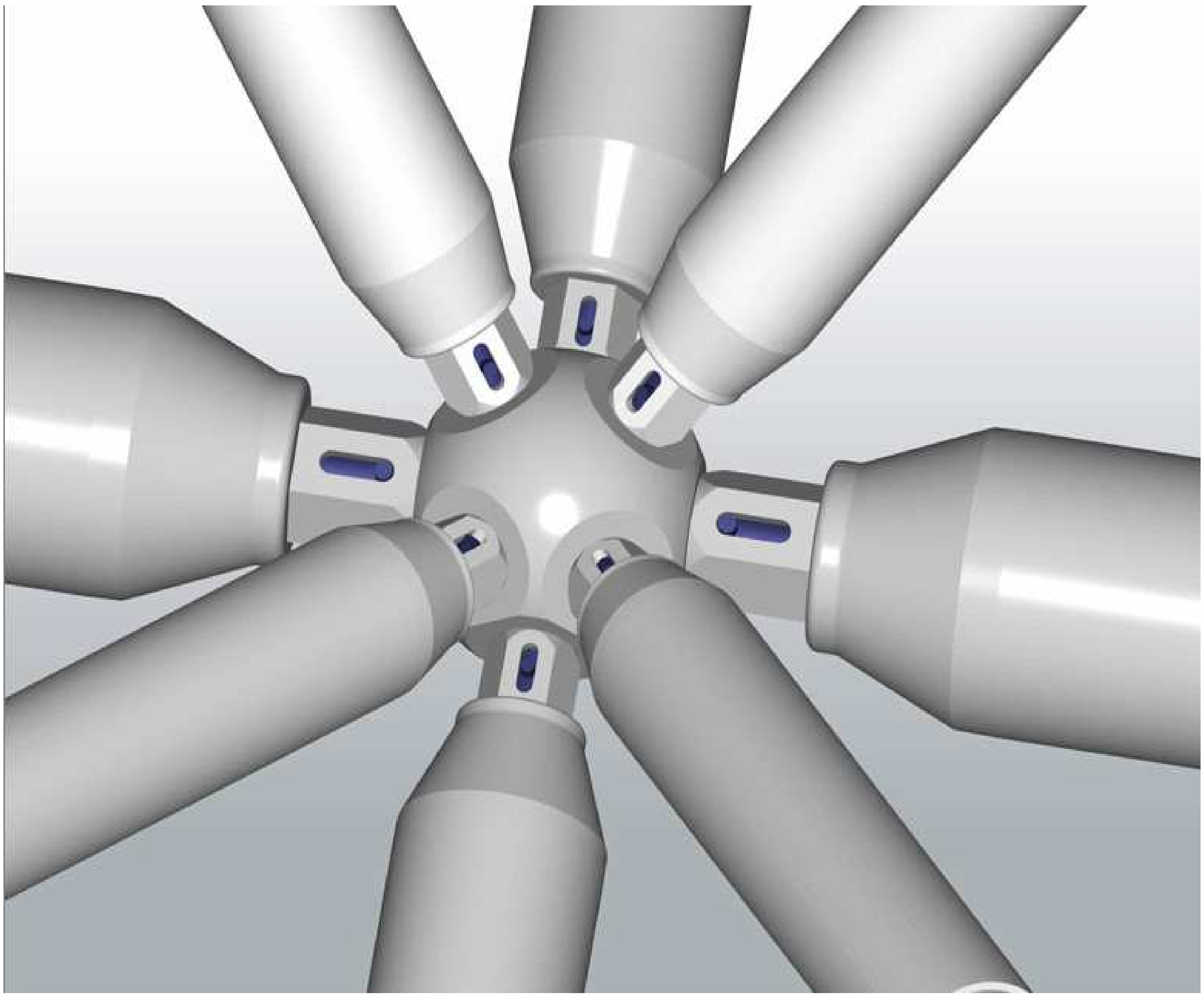


Figure 5.25 Typical Mero system

This system consists of nodes and tubes of different sizes. The basic principle is that suitable nodes and tubes are chosen from the range according to the load to be carried.

The nodes of Mero system consist of solid forged steel spheres-chosen from a limited range. Threaded holes are cut in the sphere. Three types of node exist: standard node, regular node and spherical node.

Figure 5.26 Typical Mero node

The standard node has 18 surfaces giving connecting angles at 45^0, 60^0, 90^0 and multiples of these. The regular node has 10 faces, has as many holes as are required for the frequently occurring grids. The special node has bores at any required angle. The minimum angle between two adjacent holes is 35^0. These nodes are available in seven sizes. The smallest has a diameter of 50 mm. this gives 46 mm between any two parallel faces of the maximum eighteen faces which forms the standard forged ball. The six other sizes are 85, 110, 130, 150, 190 and 240 mm. in order to improve seating of the spanner sleeve and enhance the quality of tolerance with respect to series production, the sphere has flat surface around the threaded holes, which are manufactured by milling machines.

The Mero tubes or bars generally consist of tubular or square hollow sections with truncated conical end fittings, which are welded to both ends of tubular members. These bars are connected to the threaded spherical nodes by a central bolt with tightening sleeve. These bars are capable to take axial load forces of 2 to 200t. The tube lengths are available in eight lengths: 0.5 m, 0.707 m, 1.0 m, 1.25 m, 1.414 m, 2 m, 2.5 m and 2.828 m (dimension measured between ball centers). Thus any desired configuration can be built. These tubes have diameter of about 100 mm. the bolts are produced using high strength steel and are threaded. They are electronically galvanized like the nodes and are inserted from the holes near the ends of the tube. Hence, in order to insert the bolts, the tubes must have a hole near the each end.

Essentially the Mero system is the creation of special machines, able to produce with the almost accuracy the ball junctions in which tapped holes can be aligned to any required angle. All bars are fixed concentrically to the nodes, meaning that their central lines meet exactly at the center of the sphere, whatever is the angle of entry. Threaded bolts provide a simple connection between nodes and tubes; they also ensure that the structure can be dismantled and erected elsewhere. The corrosion protection of the members is done by hot dip galvanizing (inside and outside) and by powder sintering (which allows the choice of a comprehensive range of colors). The steel elements are available either zinc plated, chrome plated or spray painted. The superfluous holes in the nodes are sealed with threaded nipples or plastic push-in plugs so as to protect against internal corrosion.

- A bolt, which is inserted through a hole in the tubular member and provide through a cone welded to the end of the tube.
- A hexagonal spanner sleeve.
- A dowel pin, which goes through the threaded bolt and connects it to the spanner sleeve.

The following sequence is involved in installing the tube in the node:

- The tubes are cut to the correct lengths.
- The end cones are welded to both ends of the tube.
- The member with end cones is galvanized.
- The bolts are inserted through the holes at the end of the tubes.
- The inserted bolts are connected to the spanner sleeves by the dowel pin. The spanner sleeve is also galvanized.

- The bolts are driven into the drilled holes in the spherical ball using the spanner sleeve.
- The bolts are driven into the drilled holes in the spherical ball using the spanner sleeve. To improve the appearance, the holes in the tubes provided for inserting the bolts may be covered with a plastic cap.

5.7 SUMMARY

The main internal forces in the case of space trusses are axial forces. From the comparative study of different approximate analysis methods, it is found that for double layer grid the girder analogy method gives best results.

6. ANALYSIS, DESIGN & DETAILING OF DOUBLE LAYER GRID & BRACED BARREL VAULT (SPACE TRUSS)

6.1 GENERAL

There are too many approximate analysis methods for double layer grid and braced barrel vault to calculate approximate forces in members. But to carry out exact analysis one need to have knowledge of computer as well as good understanding of behavior of double layer grid and braced barrel vault system. In this chapter, the analysis, design methodology and detailing of double layer grid and braced barrel vault is described.

The analysis and design of a double layer grid and braced barrel vault can be usually divided into the following steps:

a) Choice of system
b) Form selection
c) Analysis
d) Design of element sizes and connections
e) Detailing
f) Construction

6.1.1 Choice of system

The following factors are considered during choice of system:

- Architectural requirements
- Span
- Availability of skilled labor
- Cost

6.1.2 Form selection

As mentioned in ch: 4, the form selection process means selection of appropriate shape decision. The main aim of form selection method is to create a model of the structure such that its geometry satisfies the requirements of form (shape) and equilibrium can be found. Number of layers, free span, geometric distribution of the members in and between the layers and Choice of frequency of mesh is important for reasons of resistance and cost as well as for aesthetic reasons. Choice of the geometry of the network of members directly influences behavior of the systems. In the case of space truss an examination of different geometric arrangements has confirmed the importance of adopting an arrangement where directions of the members in the two layers are set at 45^0. Choice of support conditions has a big influence on the distribution of internal forces and size of the deflections. Here for double layer grid system, the type of grid selected is two way space grids with square pyramids (square on square offset) with cornice(support condition) type of grid edge profile and for braced barrel vault the type of roof is lamella roof (diamond type).

6.1.3 Analysis

The objective of an analysis of space truss systems is to determine the values of the variables necessary for sizing purposes and for those required to size their supports. The variables generally required may be:

- Compressive and tensile forces in the members in the system.
- Node displacements.
- Values of support reactions.

The study has to be made for several cases of actions and combinations of actions. The most unfavorable cases are used as the basis for design. Different analysis methods are based on the application of equilibrium to the forces applied by the members to the nodes. The methods of analysis available can be classified as follows:

1. Method of joints
2. Method of sections
3. Displacement method

As such double layer grid and braced barrel vault are basically a form of space truss (steel structure). So they are very light structure compared to typical concrete structures. So here the main primary lateral load is wind rather than seismic. During analysis the structure is subjected to different loading combinations. As mentioned in chapter no 4, here also the Primary loads are dead load, live load, wind load and earthquake load. Analysis of the structure under static and dynamic loading is performed.

6.1.4 Design of space truss systems

As such, all space trusses now a days are constructed using steel tubes and RHS sections. To design steel tube and RHS members IS: 806:1968 and IS 1161:1998 and TATA steel manual is used respectively. The general method for the design and construction of the double layer grid and braced barrel vault shown in figure 6.1

6.1.5 Construction

General Methods of construction used for space trusses may be listed in three categories:

1) Erection of separate members: - each member lifted into position and connected to the work already assembled.

2) Erection of sub-assemblies: - this is an intermediate stage whereby the members are connected in sub-assemblies.

3) Lifting of the whole space structure: - this is the final stage in which it is assembled on the ground on site. Various methods may be considered ranging from the use of vertical construction parts as lifting masts to cranes.

The choice of one of these three methods depends on:

- Type of structure and size.
- Operational conditions: actual layout of the site, available means of lifting, transport costs, experience, etc.
- Safety.

In 1) and 2) it is essential to predict the need for any temporary supports that may be necessary where the structure achieves stability only when it is complete. The many phases in erection should be carefully examined so as to avoid intermediate structural behavior which is less favorable than that for the final state of the structure.

Lifting the whole space frame has the following advantages:

- The greater part of the work is carried out on the ground. So aiding control of the operation especially the making of welded joints.

- The use of heavy hoisting machinery is required for a shorter period, which may reduce final costs.
- In some cases, the structure with other equipment attached may be lifted together.

6.2 DOUBLE LAYER GRID

6.2.1 Preliminary data for analysis

As such to start with the problem preliminary data considered as follows:

DATA:

Type of Grid:	Square on square
Type of column condition:	Cornice
Location:	Rajkot
Width of structure:	40 m
Length of structure:	60 m
Height of structure:	18 m
Module size along width direction:	2.0 m
Module size along length direction:	2.0 m
Height of grid:	2.0 m
Seismic zone:	III
Basic wind speed:	39 m/s
C/C spacing between two columns:	4.0 m
Width of column:	0.30 m
Length of column:	0.60 m
Depth of foundation:	3.0 m
Type of footing:	Isolated
Soil bearing capacity:	350 kN/m^2
Roofing material:	Structural steel tube
Cladding material:	G.I. sheet

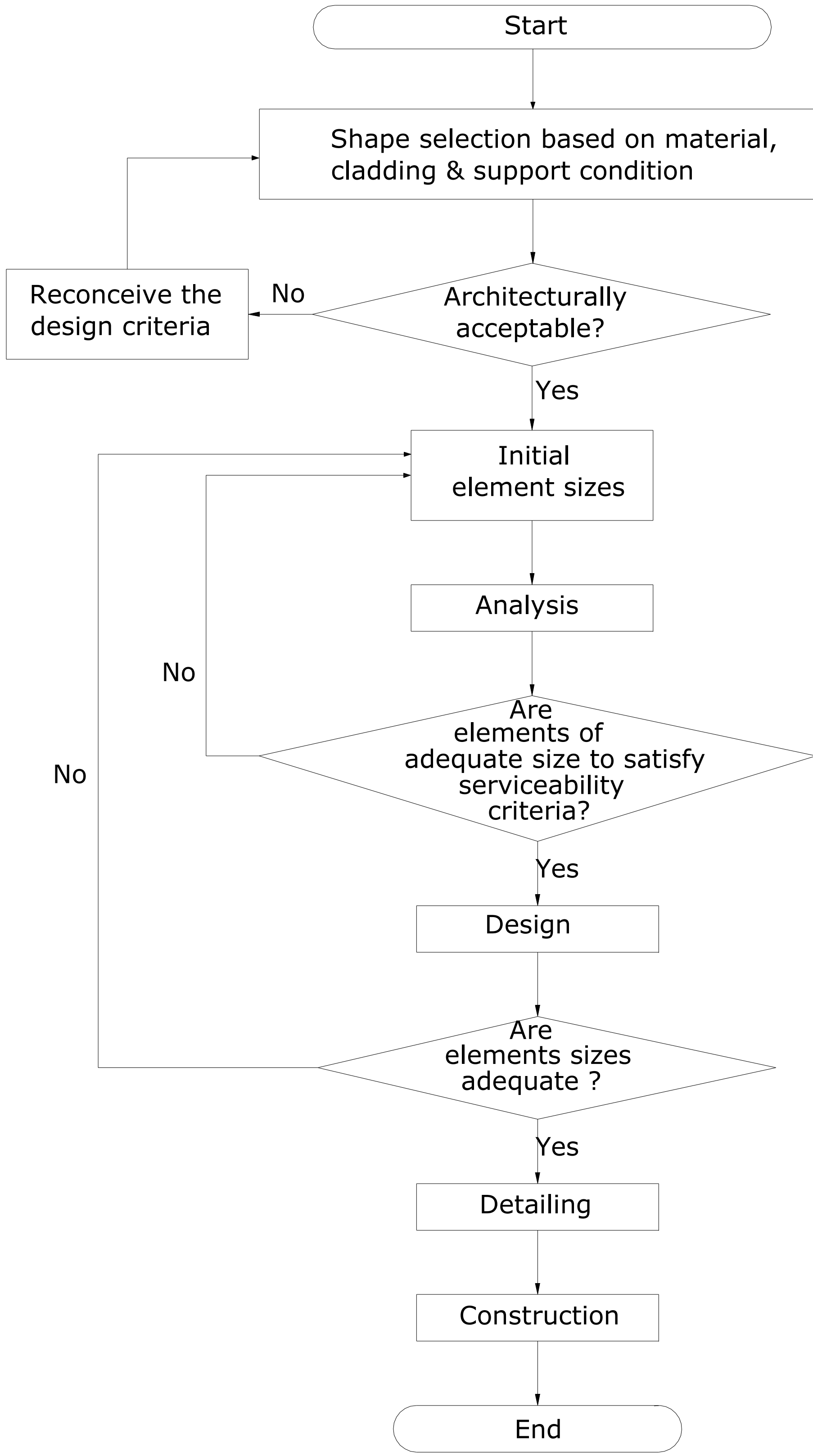


Figure- 6.1 Flow chart for general design approach of double layer grid and braced barrel vault structures

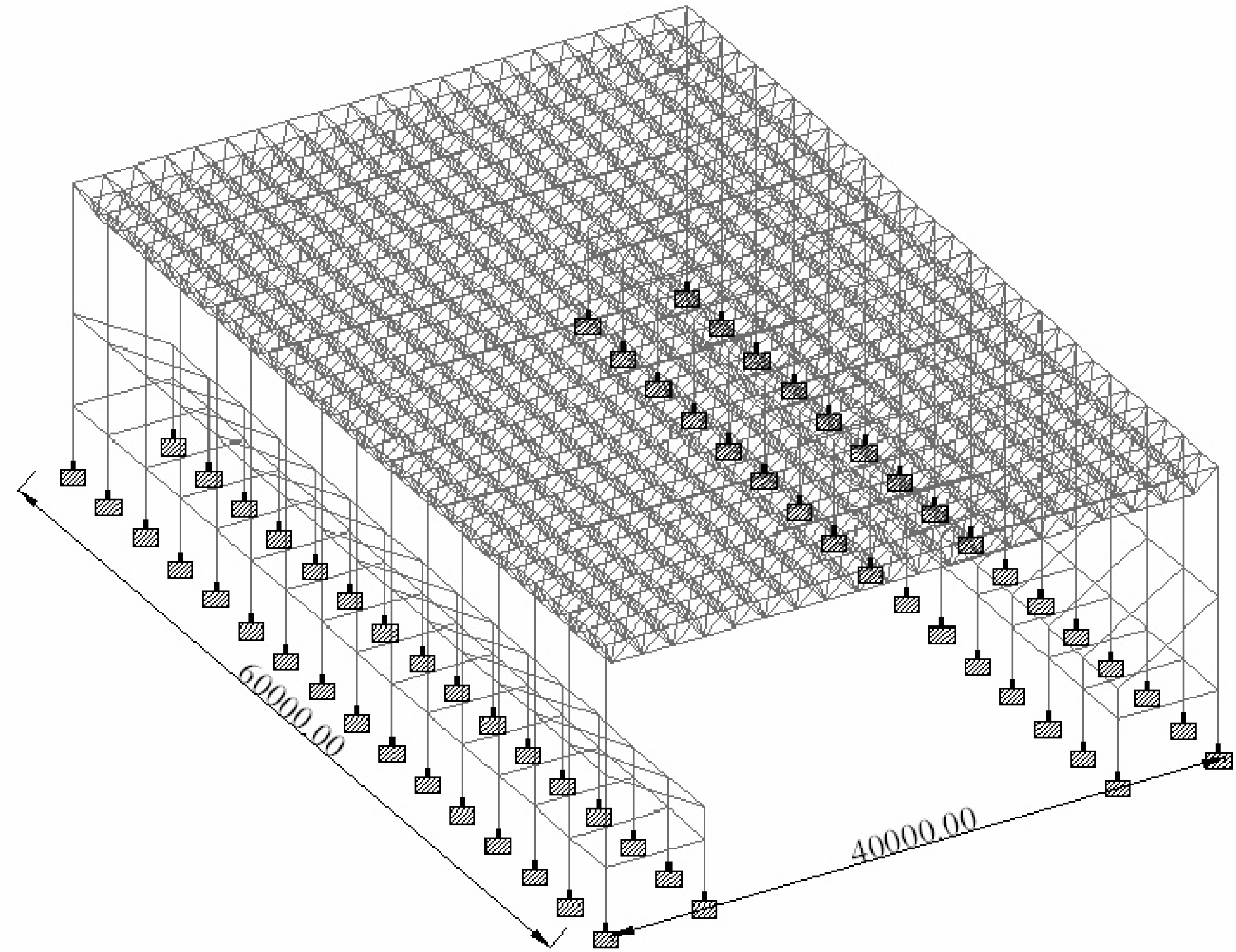


Figure 6.2 3d view of double layer grid

6.2.2 Load calculation

6.2.2.1 Dead Load: self weight + 0.15 kN/m^2

(Additional fixtures like cladding, piping system, weight of nodes, lighting system etc.)

6.2.2.2 Live Load: 0.75 kN / m^2

(IS: 875-PART (II) TABLE-2 for roof where access is not provided except for maintenance.)

6.2.2.3 Wind Load: [Appendix: A]

Table 6.1 Wind load for double layer grid structure

Load Condition	Pressure or Suction	Long Wall (kN/m²)	Short wall (kN/m²)	Roof (kN/m²)
Static	Pressure	1.03	1.03	0.086
	Suction	-0.86	-0.94	-1.12
Dynamic	Pressure	0.72	0.73	------
	Suction	-0.52	-0.62	-0.83

Wind load on roof = -1.206 kN / m^2

Wind load on long side walls (inner) = $(1.03+0.86)$ kN / m^2

C/C Distance between two columns = 4.0 m

Load on long wall (inner column) = 7.56 kN/m

Load on long wall (outer column) = 3.78 kN/m

6.2.2.4 Earthquake load: [Appendix: A]

Total base shear: 620 kN

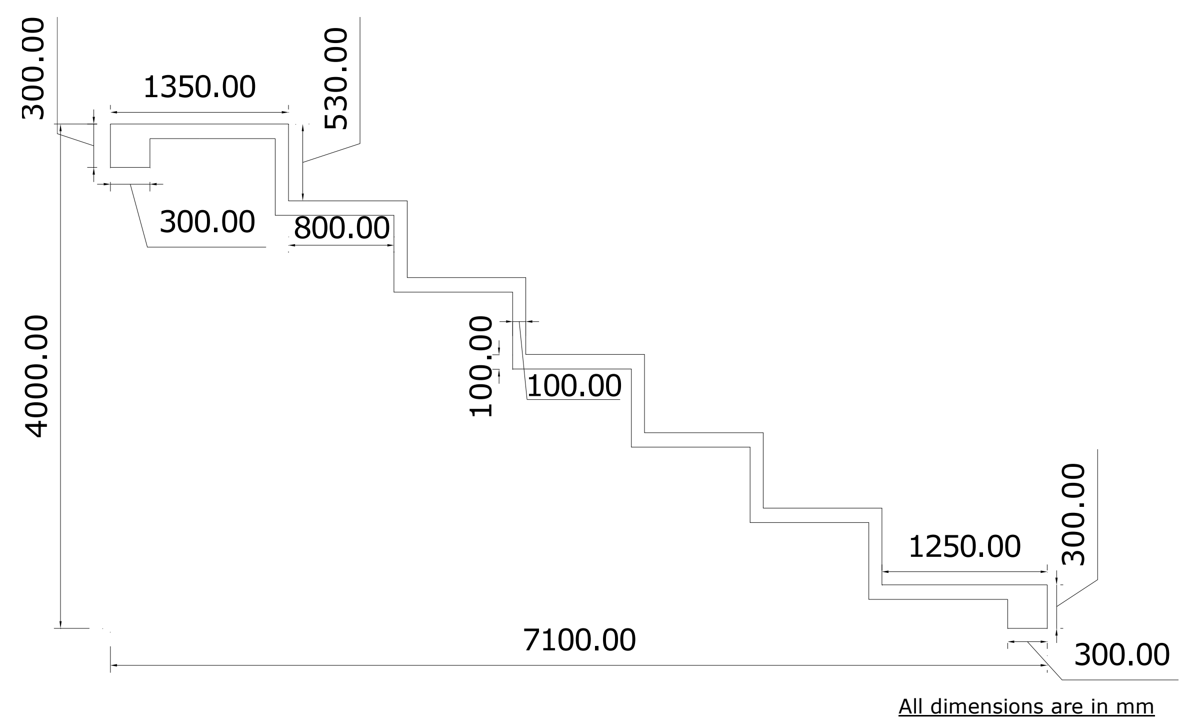


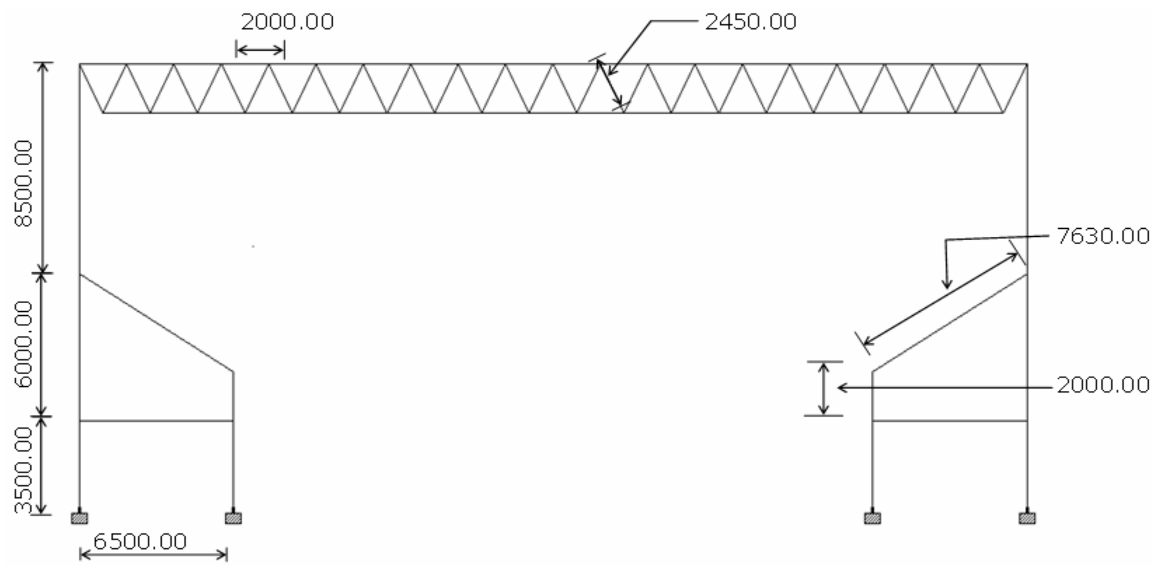
Figure 6.3 Elevation of sitting gallery

6.2.2.5 Calculation of sitting gallery:

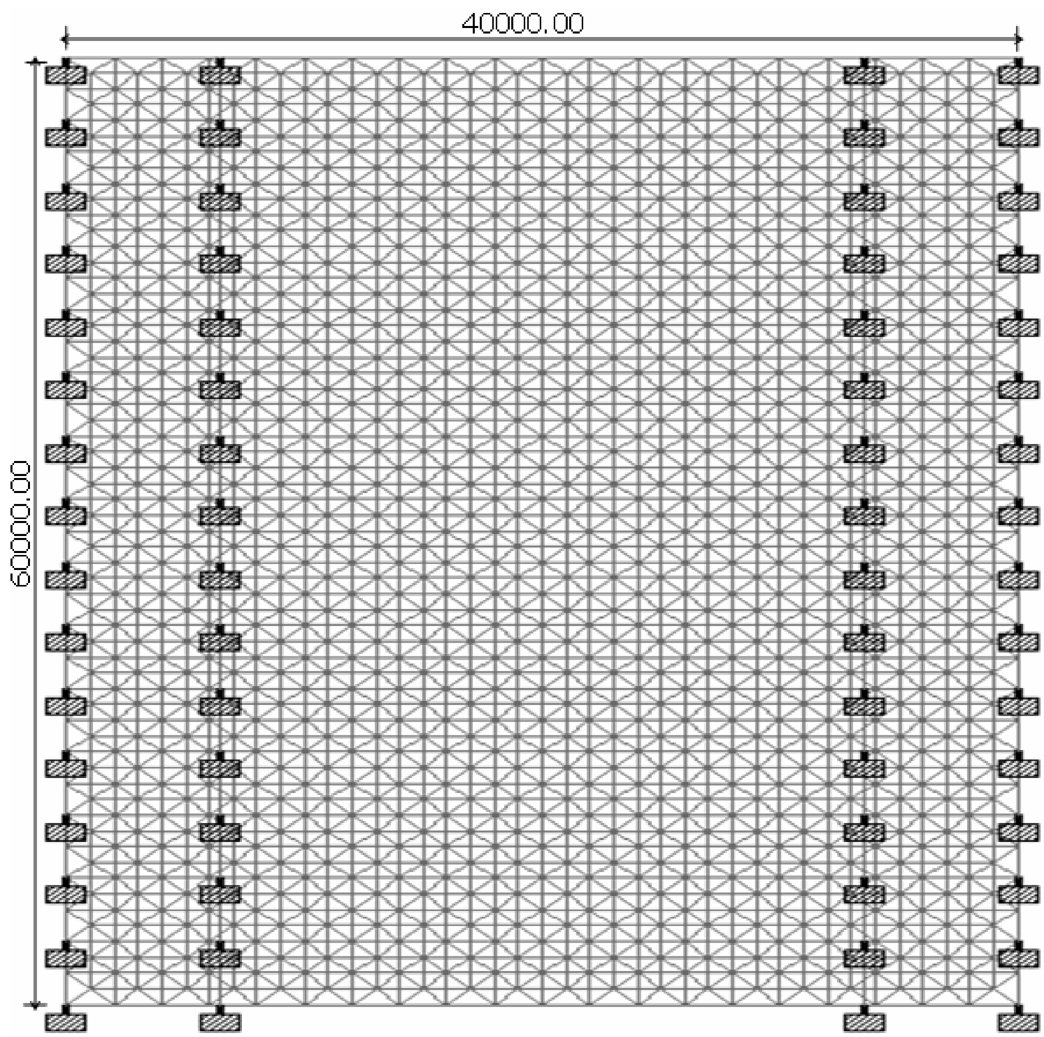
Self Weight of 100 mm thick slab	=	0.1 X 25
	=	2.5 kN/m^2
Live load	=	5.0 kN/m^2
Floor finish	=	1.0 kN/m^2
Total load on slab panel	=	8.5 kN/m^2
UDL on each slab panel	=	8.5 kN/m
Reactions	=	8.5 X 4/2
	=	17.00 kN
Weight of one step	=	0.43 X 0.1 X 2 X 25
	=	2.15 kN
Total	=	19.15 kN
No. of point load on Entire beam	=	7 No.
Total load on beam	=	19.15 X 7
	=	134.05 kN (outer)
	=	268.10 kN (Inner)
Load/m of beam	=	(134.05/7.63)
	=	17.56 kN/m (outer)
	=	35.13 kN/m (Inner)
Self weight of beam	=	0.3 X 0.6 X 25
	=	4.50 kN/m
Total UDL on inner beam	=	39.63 kN/m
Total UDL on outer beam	=	22.06 kN/m

6.2.3 Load combination

Double layer grid structure is the combination of steel and R.C.C. Roof is made from structural steel and supporting system is made of R.C.C. So as mentioned in chapter-4, load combination is selected for roof as per IS 800:1984 and for supporting structure the load combinations for limit state of collapse as per IS 875 (Part-5): 1987 given in chapter-4 (Table-4.3).



Elevation



Plan

Figure 6.4 Layout of double layer grid

6.2.4 Analysis

The double layer grid analysis is carried out using STAAD-Pro 2005. Results are presented in tabular manner below:

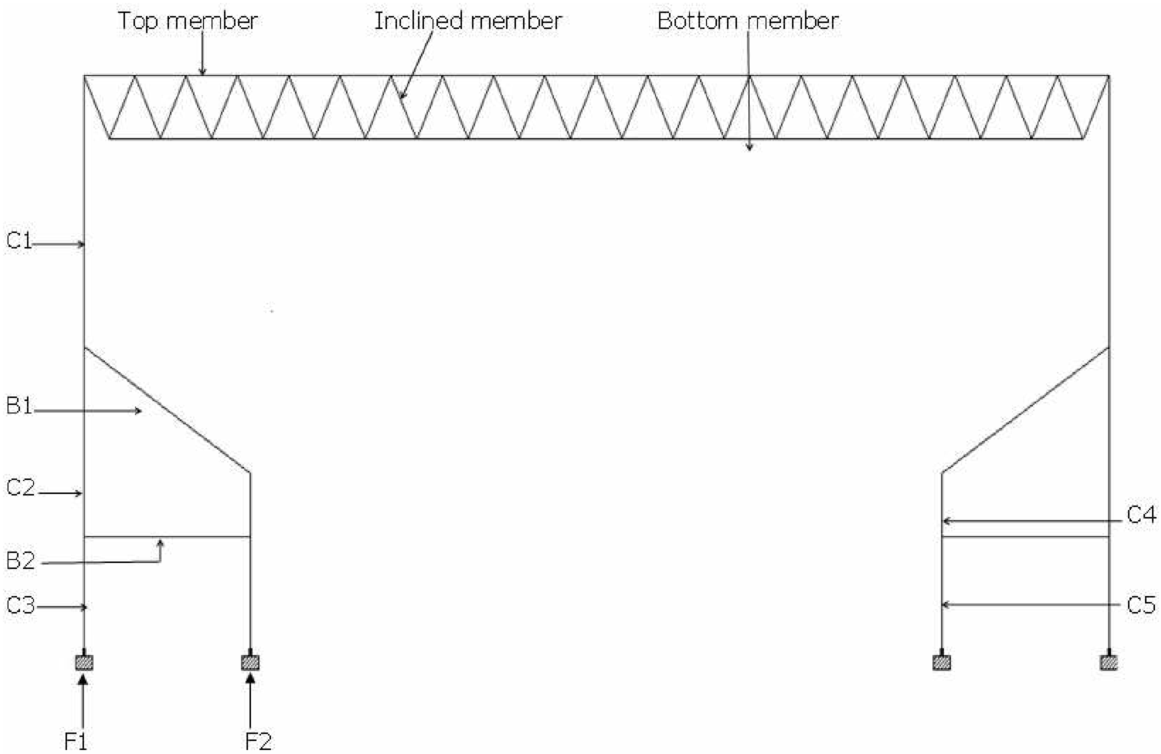


Figure 6.5 Identity of double layer grid

Table 6.2 Analysis results of double layer grid structure

Member Identity	Length of member (m)	Max Axial Forces (kN)	Min Axial Forces (kN)	Max Moment (kNm)	Min Moment (kNm)
Top	2.00	560.69	-39.24	---	---
Bottom	2.00	51.27	-606.53	---	---
Inclined	2.45	86.68	-111.42	---	---
C1	8.50	325.88	-31.58	231.90	-186.30
C2	6.00	726.29	100.693	251.80	-252.00
C3	3.50	860.96	156.81	234.50	-152.50
C4	2.00	402.94	51.23	279.90	-194.70
C5	3.50	493.20	50.96	182.50	-131.80
B1	7.63	324.91	-254.81	343.90	-217.70
B2	6.50	38.89	-100.03	221.20	-209.70

Table 6.3 Deflection of double layer grid

Structural system	Max Vertical deflection (mm)	Allowable Deflection (mm)	Max Horizontal deflection (mm)	Allowable Deflection (mm)	Remarks
Double layer grid	119.87	123.07	43.67	55.38	O.K

Table 6.4 Reactions at footing of double layer grid structure

Structural system	Footing Identity	Horizontal FX (kN)	Vertical FY (kN)	Moment MZ (kNm)
Double layer grid	F1	101.972	860.964	-234.374
		-50.604	179.077	98.171
		-78.479	256.159	152.515
		102.054	860.020	-234.530
	F2	-56.988	493.201	131.283
		28.720	68.777	-101.146
		-57.097	492.901	131.761
		54.680	182.093	-182.517

6.2.5 Design

6.2.5.1 Roof:

Material: structural steel tube.

Grade of steel: Yst 32

Permissible axial stress in tension: 190 N/mm^2

Table 6.5 Roof design schedule

Member Identity	Length of member (m)	Nominal dia of bore (mm)	Outside dia of bore (mm)	Class	Thk. (mm)	Weight (kg/m)	Area of c/s (cm^2)	Radius of gyration (cm)
Top	2.00	200	219.10	Heavy	5.9	31.0	39.50	7.54
Bottom	2.00	175	193.70	Heavy	5.9	27.3	34.82	6.64
Inclined	2.45	50	60.30	Heavy	4.5	6.19	7.88	1.98

6.2.5.2 Column:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 6.6 Column design schedule

Member Identity	Length of member (m)	Size (mmxmm)	Vertical steel (Nos.-dia)	Sp. Confi. hoops through out column (#, mm c/c)	Sp. Confi. hoops up to length "lo" (#, mm c/c)	Length "lo" (mm)	Hoops beyond length "lo" (#,mm c/c)
C1	8.5	300 X 600	12- #16	------	#8, 100	1370	#8, 200
C2	6.0	300 X 600	12- #16	------	#8, 100	900	#8, 200
C3	3.5	300 X 600	12- #16	#8, 100	------	-----	------
C4	2.0	300 X 600	8- #16 + 4- #20	------	#8, 100	600	#8, 200
C5	3.5	300 X 600	8- #16 + 4- #20	#8, 100	------	-----	------

6.2.5.3 Beam design schedule:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 6.7 Beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
B1	7.63	300 X 600	3- #32	3- #32
B2	6.50	300 X 600	2- #32	2- #32

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	100	1120	8	200	4790	8	100	1120
8	100	1120	8	200	3660	8	100	1120

6.2.5.4 Sitting gallery schedule:

Grade of steel: Fe 415

Grade of concrete: M 20

Table 6.8 Sitting gallery beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
Beam	4.00	100 X 630	2- #10	2- #8

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	200	1200	8	250	600	8	200	1200

Table 6.9 Sitting gallery slab design schedule

Member Identity	Size (mm x mm)	Thickness (mm)	Main steel (Dia-Spc mm c/c)	Distribution steel (Dia-Spc mm c/c)
SLAB	900 X 4000	100	#8-225	#6-175

6.2.5.5 Footing schedule:

Grade of steel: Fe 415

Grade of concrete: M 20

P.C.C thickness: 150 mm

P.C.C grade: 1:3:6

Soil bearing capacity: 350 kN/m^2

Table 6.10 Footing design schedule

Member Identity	P.C.C size (mm x mm)	Footing size (mm X mm)	End Thk. "t" mm	Overall Thk. "T" mm	Short bars (dia-mm-c/c)	Long bars (dia-mm-c/c)	Remarks
F1	1670 X 1980	1370 X 1680	230	520	#16-100	#12-100	Isolated
F2	1980 X 3650	1680 X 3350	230	520	#16-100	#12-200	Isolated

6.2.6 Detailing

In this section, Detailing of double layer grid is carried out. Detail drawings regarding Beam column junctions A, B, C and D are mentioned. Connection like steel tube to concrete column, tube to Mero node is also mentioned. A 3D view of steel tube to concrete column is also prepared.

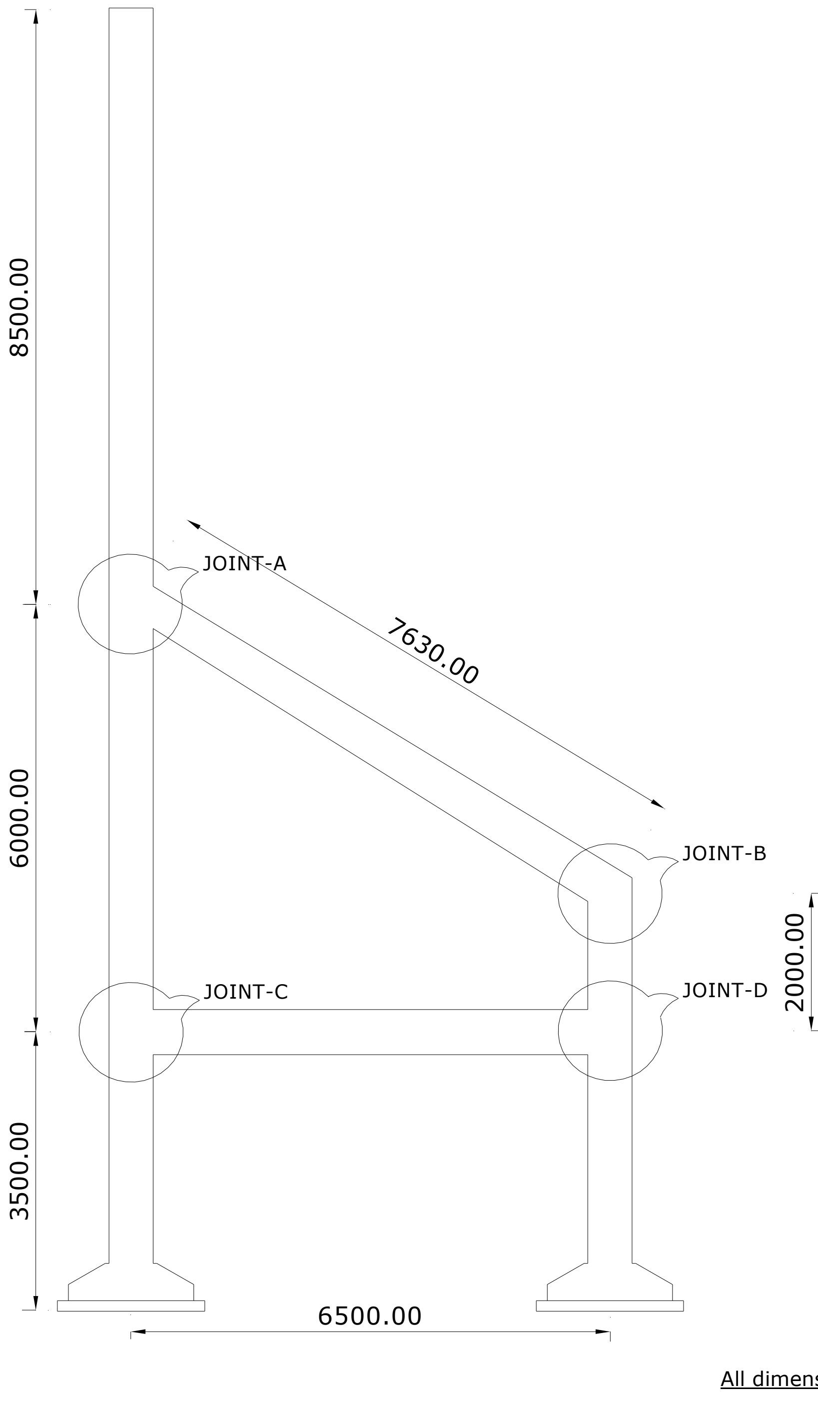
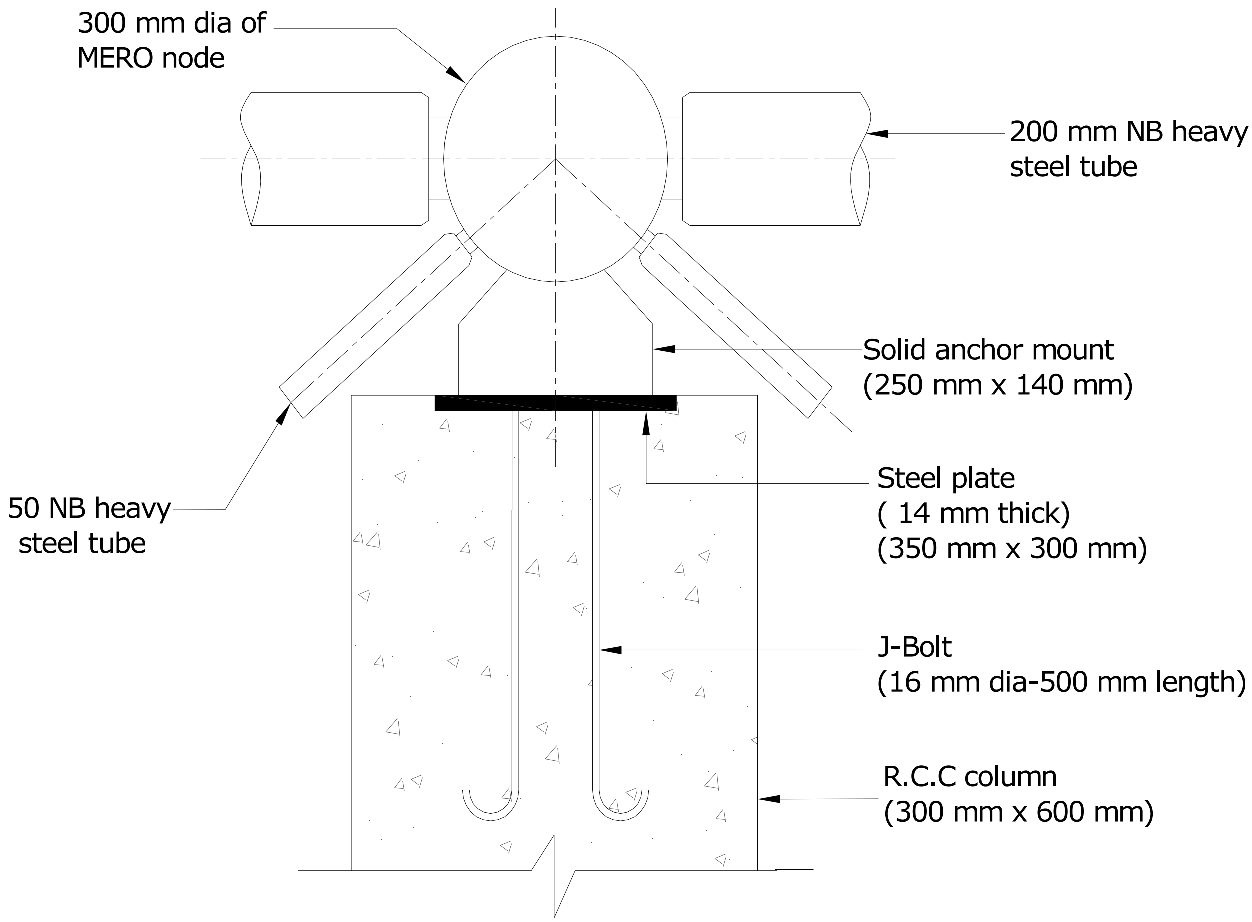
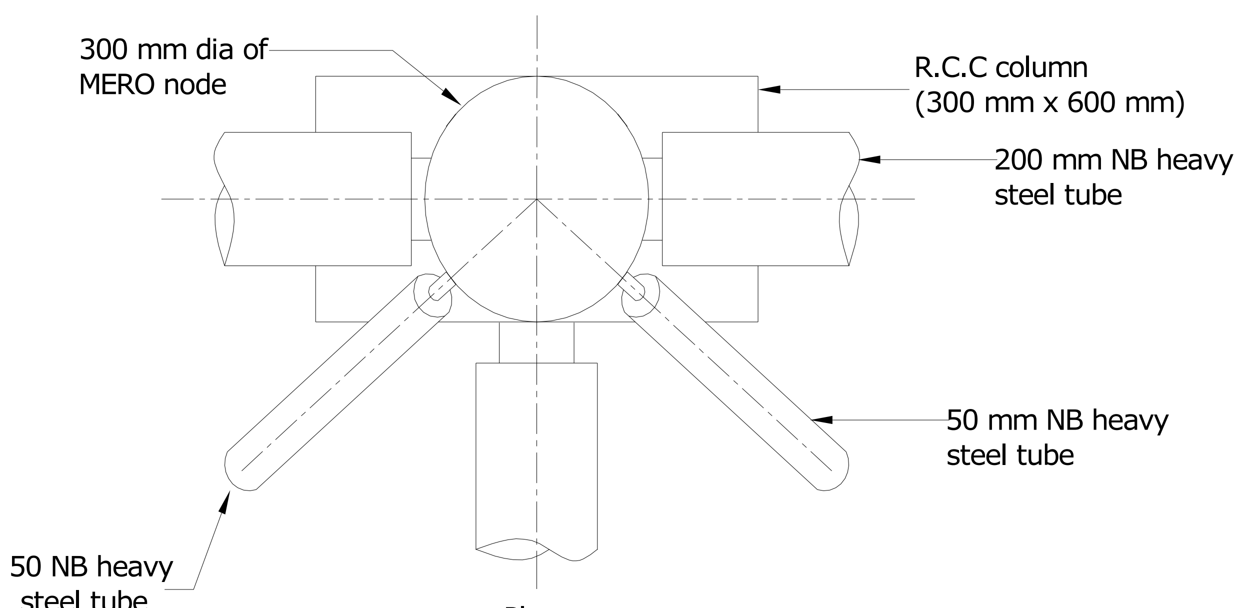


Figure 6.6 Supporting structural system modules for double layer grid



Elevation



Plan

Figure 6.7 Detail of connection of steel tube to concrete column

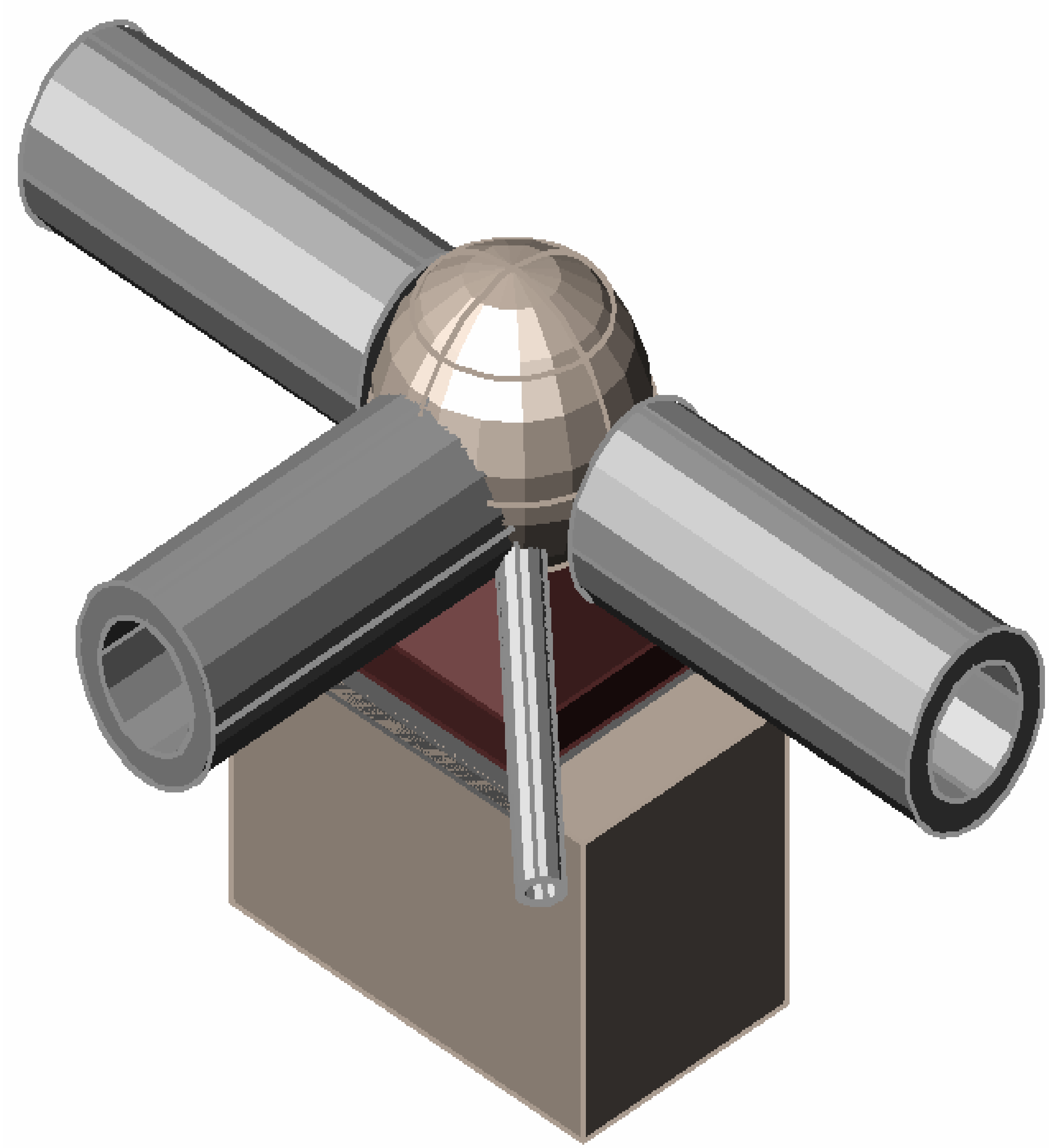


Figure 6.8 3d view of steel tube to concrete column

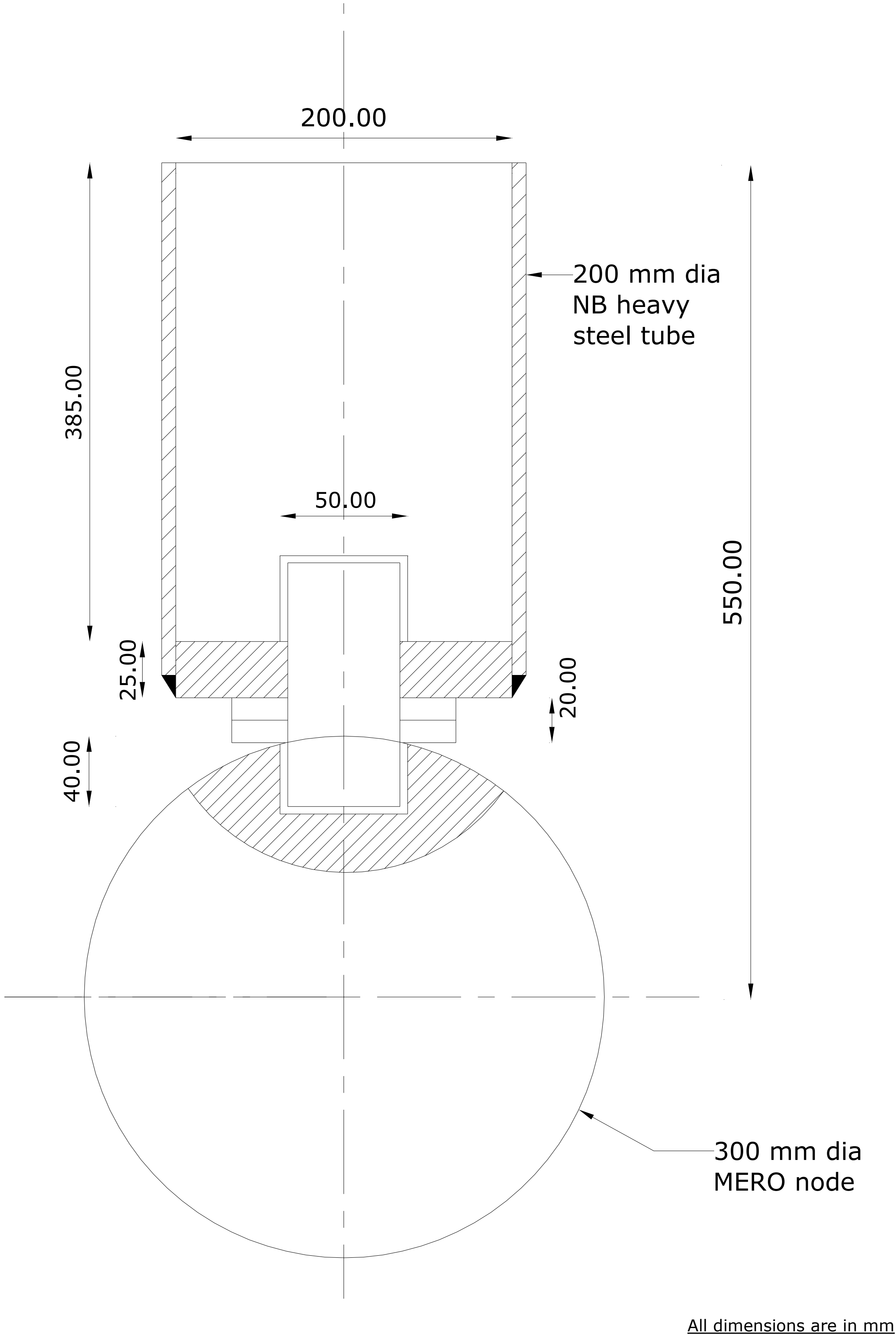


Figure 6.9 Typical stub details

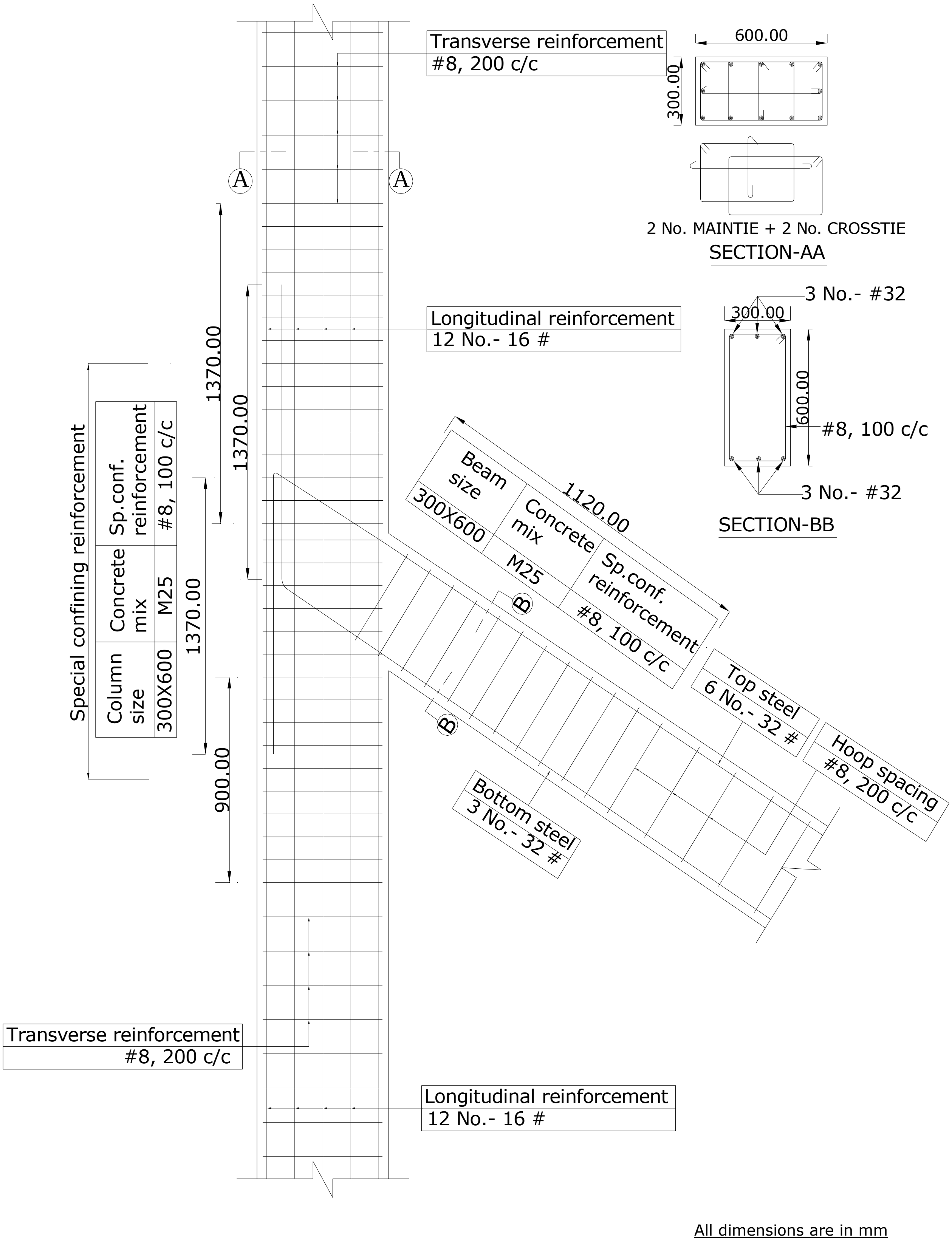


Figure 6.10 Beam-column junction (Joint-A)

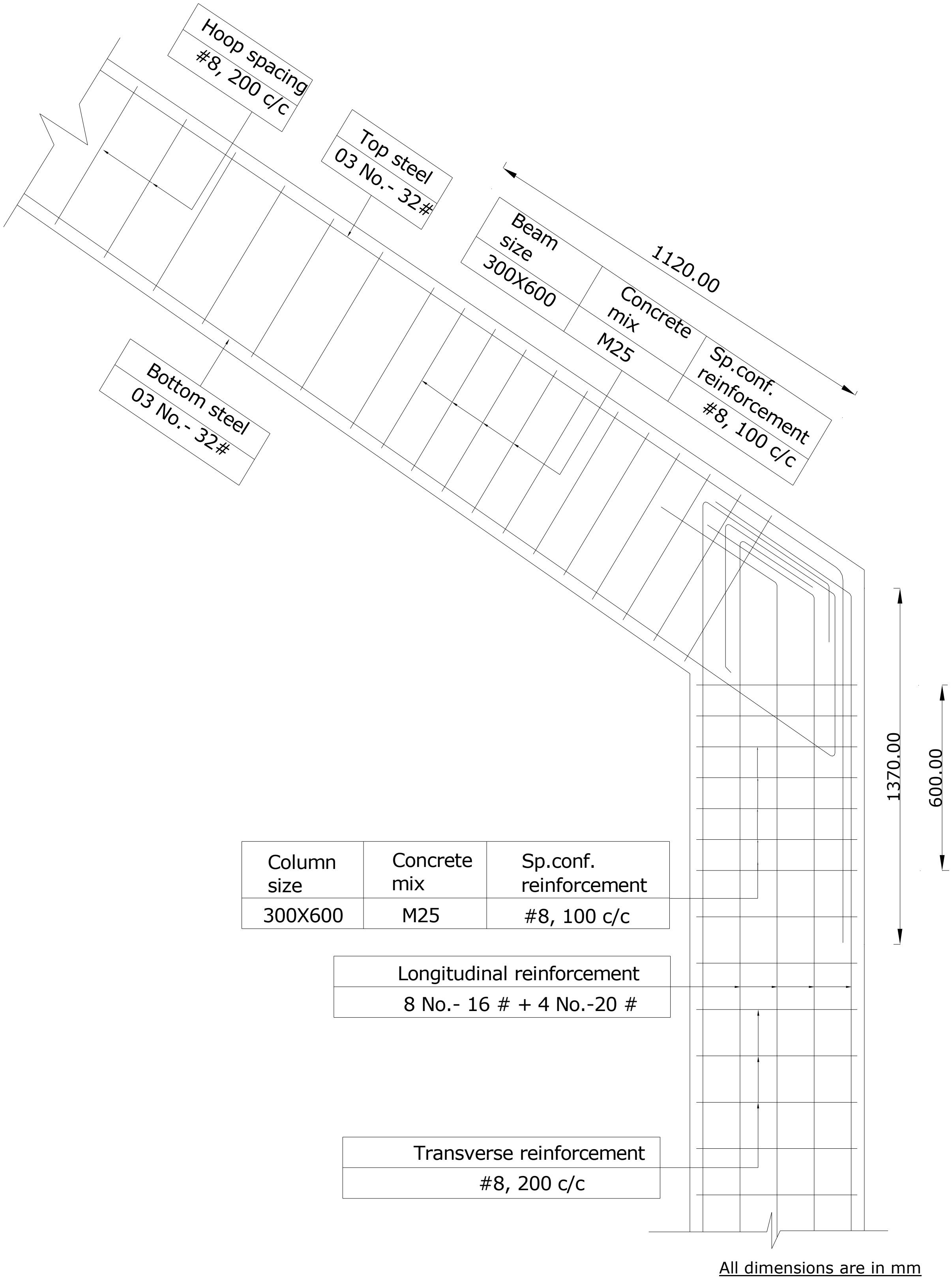


Figure 6.11 Beam-column junctions (Joint-B)

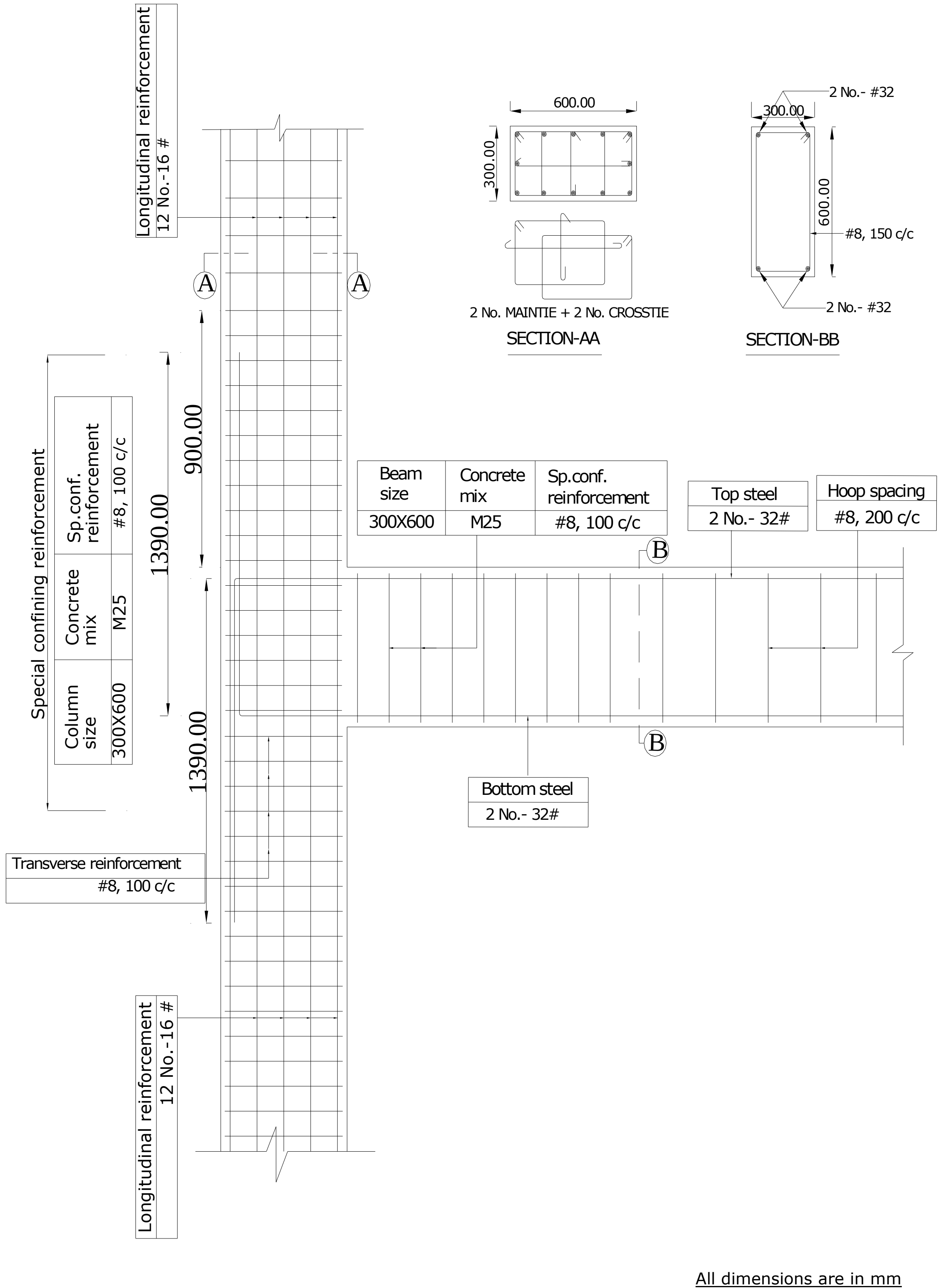


Figure 6.12 Beam-column junctions (Joint-C)

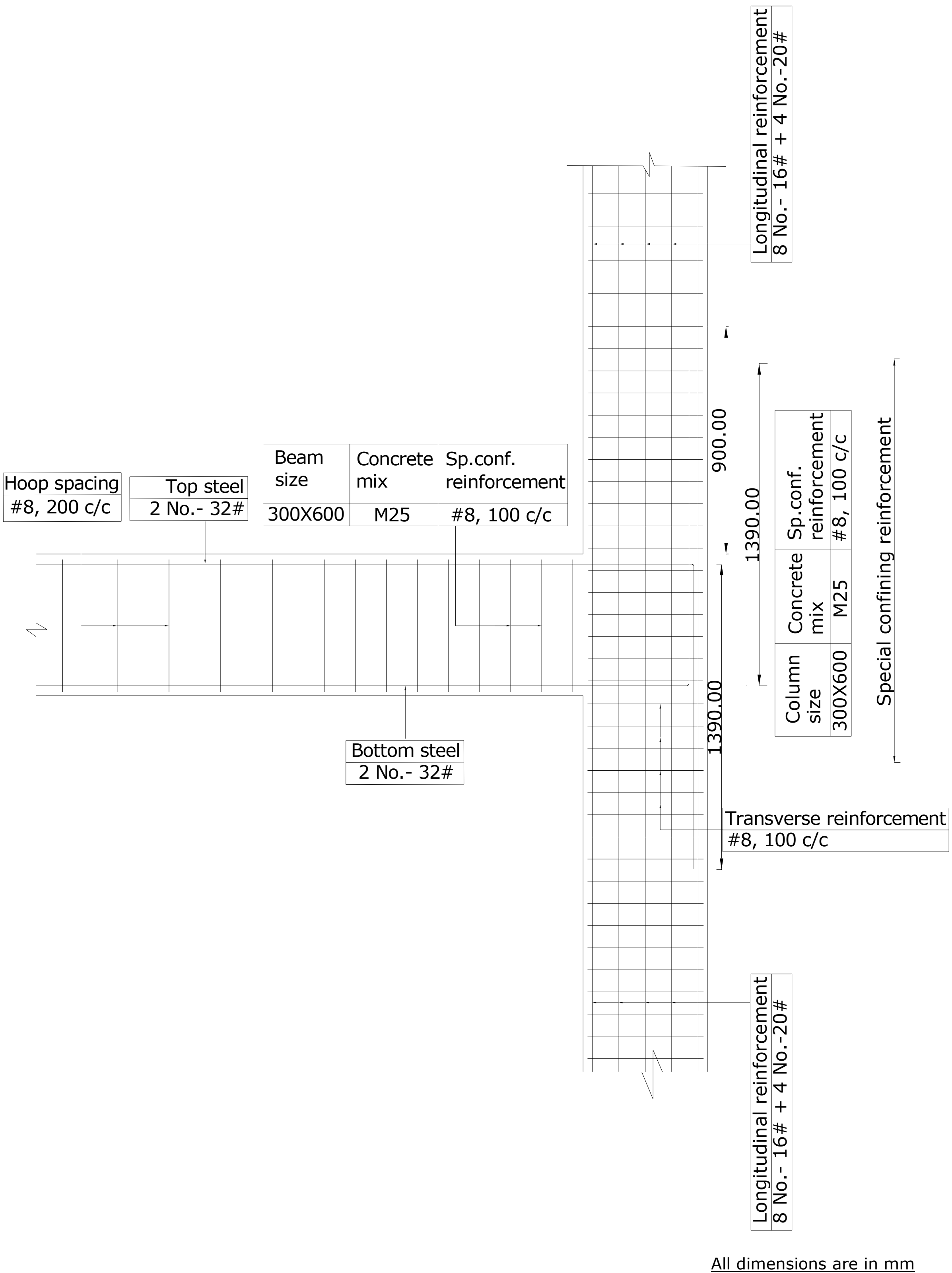


Figure 6.13 Beam-column junctions (Joint-D)

6.3 BRACED BARREL VAULT

6.3.1 Preliminary data for analysis

As such to start with the problem preliminary data considered as follows:

DATA:

Type:	Lamella
Location:	Rajkot
Width of structure:	40 m
Length of structure:	60 m
Height of structure:	18 m
Size of element along width direction:	1.5 m
Size of element along length direction:	2.0 m
Internal size of all elements:	1.25 m
Seismic zone:	III
Basic wind speed:	39 m/s
C/C spacing between two columns:	4.0 m
Width of column:	0.30 m
Length of column:	0.60 m
Depth of foundation:	3.0 m
Type of footing:	Isolated
Soil bearing capacity:	350 kN/m^2
Roofing material:	Structural steel RHS
Cladding material:	G.I. sheet

6.3.2 Load calculation

6.3.2.1 Dead Load: self weight+ 0.15 kN/m^2

(Additional fixtures like cladding, piping system, lighting system etc.) [2]

6.3.2.2 Live Load:

(As per TABLE-2) IS: 875-PART (II) for roof

Calculation: - $0.75-0.52y^2$

$Y= (h/l)^2$

$= (8/40)^2$

$= 0.04$

$= 0.75-0.52(0.04)$

$= 0.7292$ kN / m^2

6.3.2.3 Wind Load: [Appendix: A]

Table 6.11 Wind load for braced barrel vault structure

Load Condition	Pressure or Suction	Long wall-A windward side (kN/m²)	Long wall-B Leeward side (kN/m²)	Roof (kN/m²)
Static	Pressure	0.26	----	----
	Suction	-1.12	-0.94	-1.12
Dynamic	Pressure	0.82	----	------
	Suction	----	-0.62	-0.83

Wind load on roof: -1.12 kN / m^2

Load on interior element: 1.12*1.25*1.25

1.750 kN

Load shared by four elements: 1.750/ (1.25*4)

0.35 kN/m (from one side)

0.70 kN/m (one element)

6.3.2.3.1 Windward side:

Wind load on long side walls (inner): (0.26+1.12) =1.38 kN / m^2

C/C Distance between two columns: 4.0 m

Load on long wall (inner column)-A: 5.52 kN/m

Load on long wall (outer column)-A: 2.76 kN/m

6.3.2.3.2 Leeward side:

Wind load on long side walls (inner): -0.94 kN / m^2

C/C Distance between two columns: 4.0 m

Load on long wall (inner column)-B: 3.76 kN/m

Load on long wall (outer column)-B: 1.88 kN/m

6.3.2.4 Earthquake load: [Appendix: A]

Total base shear: 830 kN

6.3.2.5 Sitting gallery: [cl: 6.2.2.5]

Total UDL on inner beam: 39.63 kN/m

Total UDL on outer beam: 22.06 kN/m

6.3.3 Load combination

Braced barrel vault is a typical type of steel space structure. Here the roof is considered as made of structural steel (RHS sections) while supporting system made from R.C.C. So load combination is selected as per table Table-4.3.

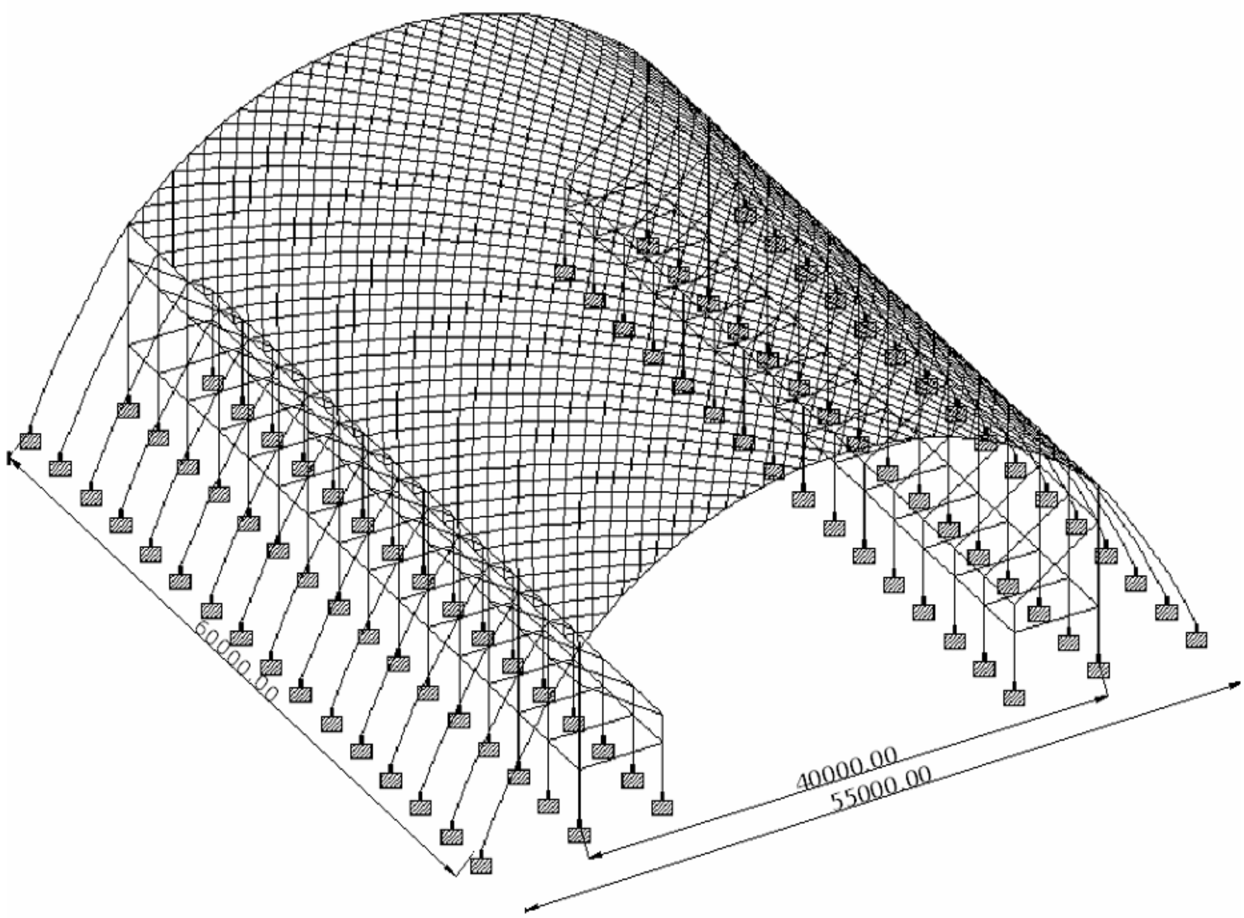


Figure 6.14 3d view of braced barrel vault

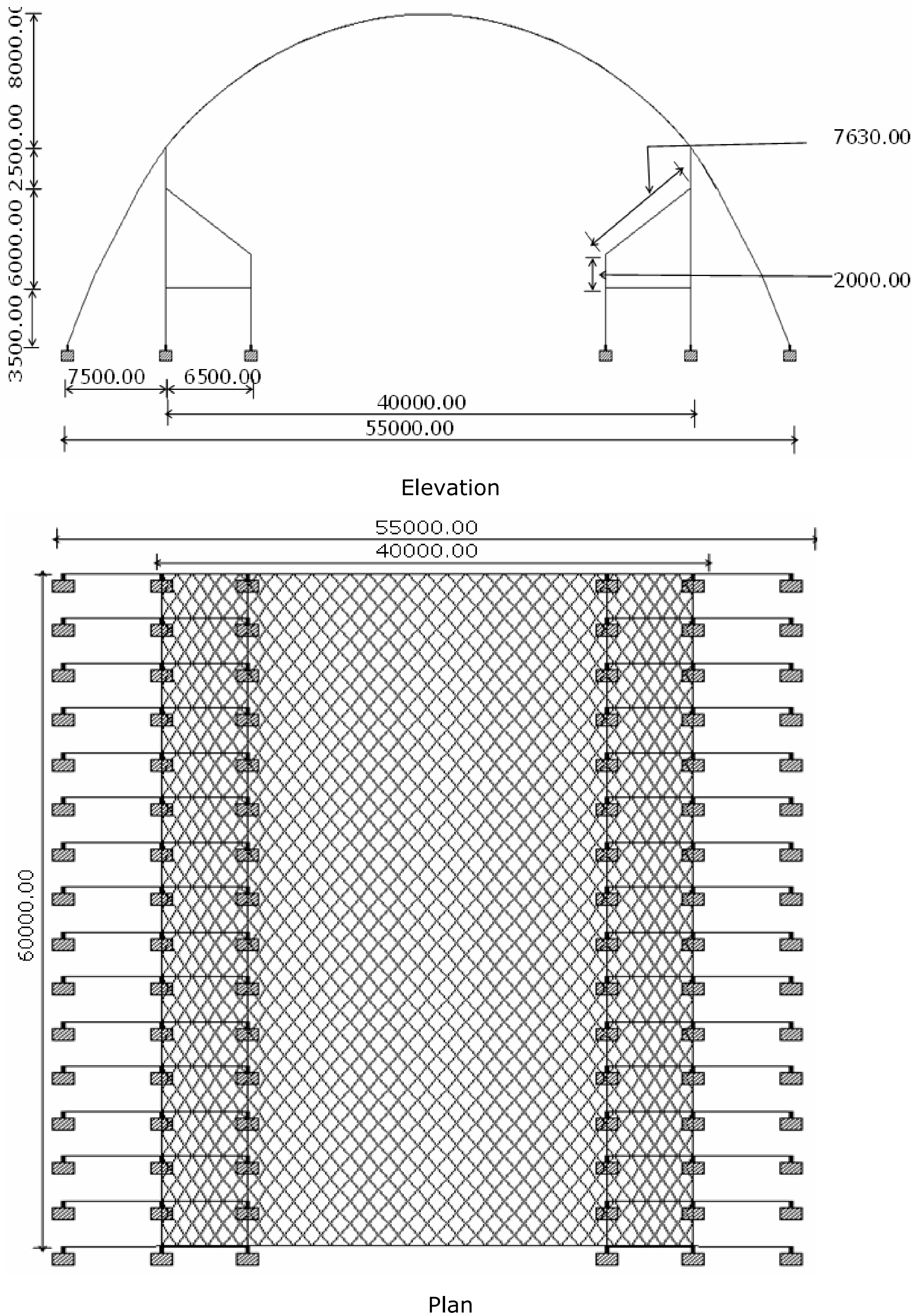
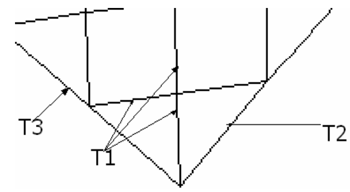


Figure 6.15 Layout of braced barrel vault

6.3.4 Analysis

Analysis of braced barrel vault is carried out using STAAD-pro 2005. After performing analysis of braced barrel vault structure, the results are presented in tabulated manner below.



Detail-X

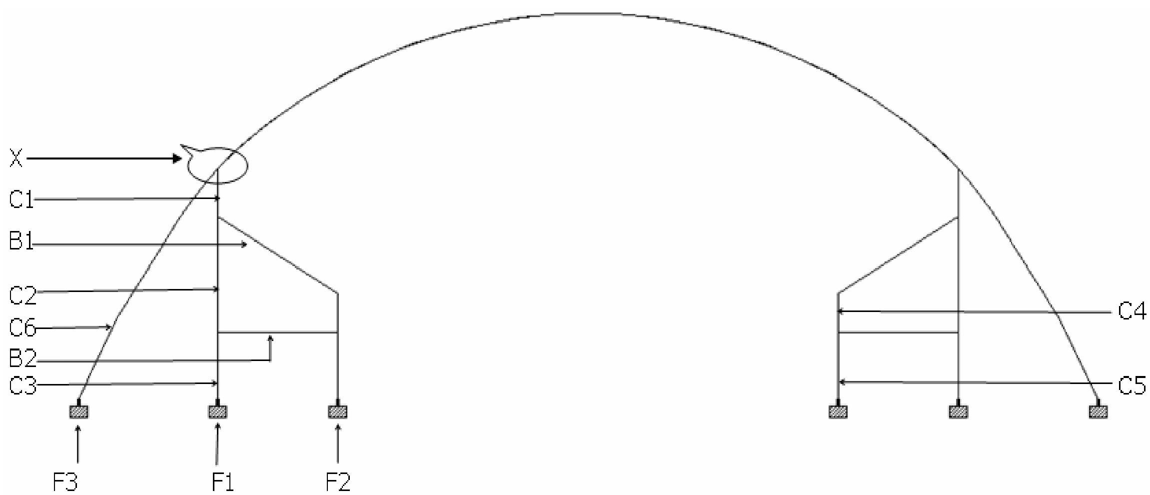


Figure 6.16 Identity of braced barrel vault

Table 6.12 Analysis results of braced barrel vault structure

Member Identity	Length of member (m)	Max Axial Forces (kN)	Min Axial Forces (kN)	Max Moment (kNm)	Min Moment (kNm)
T1	1.25	215.17	-67.49	---	---
T2	1.50	370.52	-90.84	---	---
T3	2.00	67.88	-352.57	---	---
C1	2.50	116.76	-207.69	186.19	-185.30
C2	6.00	417.14	91.32	241.76	-252.60
C3	3.50	506.77	112.62	167.79	-167.60
C4	2.00	474.19	49.15	232.00	-296.80
C5	3.50	539.29	52.32	114.07	-113.99
C6	14.50	842.87	-346.01	183.82	-219.40
B1	7.63	339.98	-204.15	378.57	-289.40
B2	6.50	61.28	-104.61	151.09	-142.10

Table 6.13 Deflection of braced barrel vault

Structural system	Max Vertical deflection (mm)	Allowable Deflection (mm)	Max Horizontal deflection (mm)	Allowable Deflection (mm)	Remarks
Braced barrel vault	108.32	123.07	44.41	55.38	O.K

Table 6.14 Reactions at footing of braced barrel vault structure

Structural system	Footing Identity	Horizontal FX (kN)	Vertical FY (kN)	Moment MZ (kNm)
Braced barrel vault	F1	-0.037	506.771	22.612
		-19.085	-25.691	40.478
		-78.387	251.843	167.788
		78.264	255.714	-167.595
	F2	-31.347	539.292	60.881
		-10.908	-47.105	35.080
		-28.663	75.778	114.066
		28.647	76.078	-113.986
	F3	-432.972	727.026	218.528
		204.798	-327.863	-120.438
		-432.973	726.665	219.354
		432.150	725.304	-218.960

6.3.5 Design

6.3.5.1 Roof:

Material: Structural Rectangular hollow section

Grade of steel: Yst 32

Permissible axial stress in tension: 190 N/mm^2

Table 6.15 Roof design schedule of BBV

Member Identity	Length of member (m)	D X B (mmxmm)	Thk. (t) mm	C/S Area (cm^2)	Unit Wt. (w) kg/m	M.O.I (Ixx) (cm^2)	M.O.I (Iyy) (cm^2)	Radius of gyration (cm)
T1	1.25	260 X 180	4.0	34.15	26.81	3357.53	1987.45	7.49
T2	1.50	260 X 180	4.0	34.15	26.81	3357.53	1987.45	7.49
T3	2.00	260 X 180	4.0	34.15	26.81	3357.53	1987.45	7.49

6.3.5.2 Column schedule:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 6.16 Column design schedule of BBV

Member Identity	Length of member (m)	Size (mmxmm)	Vertical steel (Nos.-dia)	Sp. Confi. hoops through out column (#, mm c/c)	Sp. Confi. hoops up to length "lo" (#, mm c/c)	Length "lo" (mm)	Hoops beyond length "lo" (#, mm c/c)
C1	2.5	300 X 600	12- #16	------	#8, 100	600	#8, 200
C2	6.0	300 X 600	12- #16	------	#8, 100	900	#8, 200
C3	3.5	300 X 600	12- #16	#8, 100	------	-----	------
C4	2.0	300 X 600	12- #16	------	#8, 100	600	#8, 200
C5	3.5	300 X 600	12- #16	#8, 100	------	-----	------
C6	14.50	300 X 600	4- #16 + 8-#12	#8, 100	#8, 100	2320	#8, 150

6.3.5.3 Beam schedule:

Grade of steel: Fe 415

Grade of concrete: M 25

Table 6.17 Beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
B1	7.63	300 X 600	3- #32	3- #32
B2	6.50	300 X 600	2- #32	2- #32

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	100	1120	8	200	4790	8	100	1120
8	100	1120	8	200	3660	8	100	1120

6.3.5.4 Sitting gallery schedule:

Grade of steel: Fe 415

Grade of concrete: M 20

Table 6.18 Sitting gallery beam design schedule

Member Identity	Length of member (m)	Size (mm x mm)	Bottom steel (Nos.-dia)	Top steel (Nos.-dia)
Beam	4.00	100 X 630	2- #10	2- #8

Stirrups								
Left			Center			Right		
Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)	Dia (mm)	Spacing (mm c/c)	Distance (mm)
8	200	1200	8	250	600	8	200	1200

Table 6.19 Sitting gallery slab design schedule

Member Identity	Size (mm x mm)	Thickness (mm)	Main steel (Dia-Spc mm c/c)	Distribution steel (Dia-Spc mm c/c)
SLAB	900 X 4000	100	#8-225	#6-175

6.3.5.5 Footing schedule:

Grade of steel: Fe 415

Grade of concrete: M 20

P.C.C thickness: 150 mm

P.C.C grade: 1:3:6

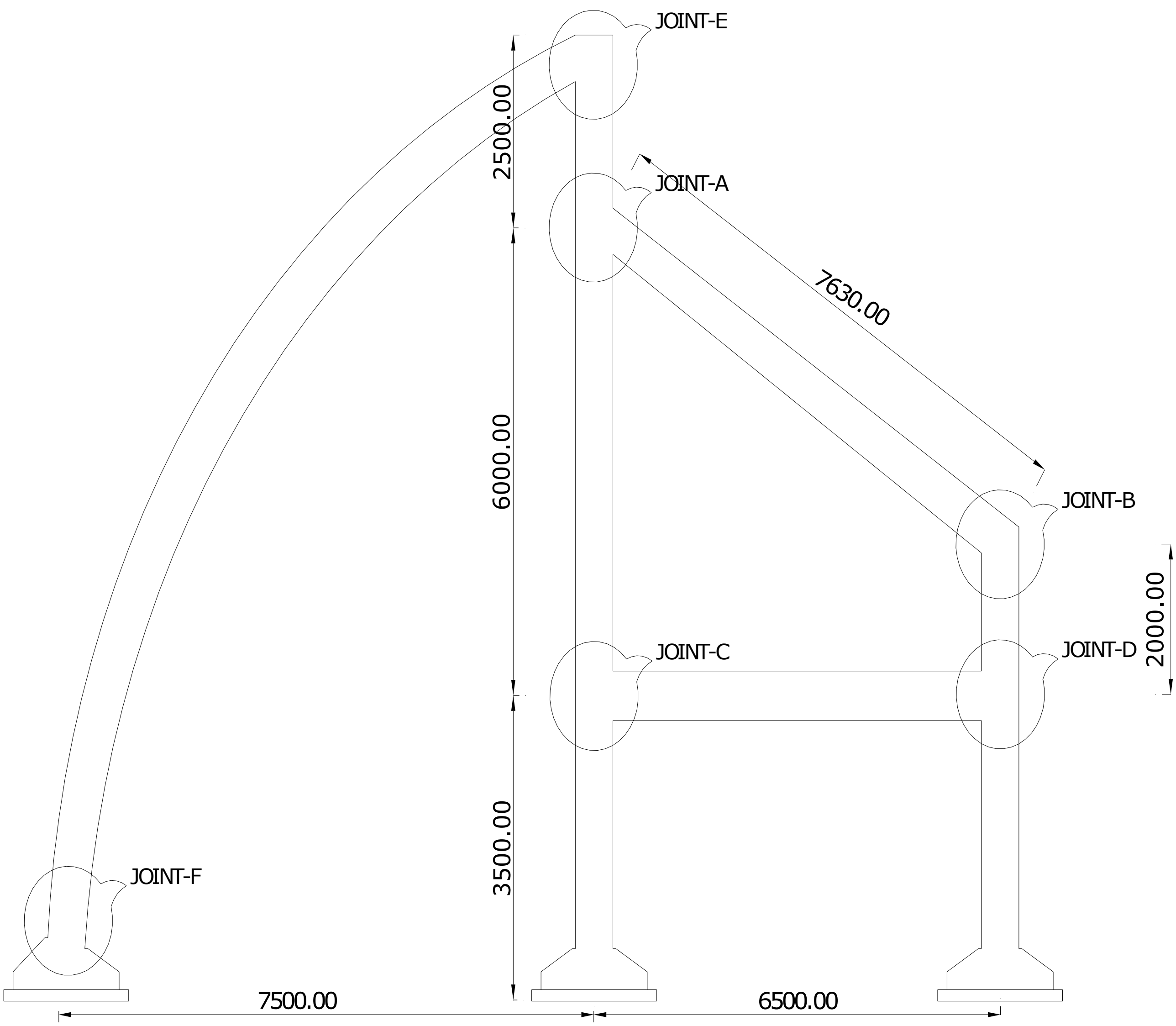
Soil bearing capacity: 350 kN/m^2

Table 6.20 Footing design schedule

Member Identity	P.C.C size (mm X mm) (BXD)	Footing size (mm X mm)	End Thk. "t" mm	Overall Thk. "T" mm	Short bars (dia-mm-c/c)	Long bars (dia-mm-c/c)	Remark
F1	1980 X 3350	1680 X 3050	230	520	#16 -100	#12 -100	Isolated
F2	1980 X 3350	1680 X 3050	230	520	#16 -100	#12-100	Isolated
F3	1520 X 1980	1320 X 1680	230	520	#16 -125	#12-100	Isolated

6.3.6 Detailing:

In this section, Detailing of braced barrel vault is carried out. As such detailing of Joint-A, B, C and D is same as that of the double layer grid. Detailed drawing of sitting gallery slab-beam connections and isolated footing mentioned earlier in this chapter. So here in this section detailing regarding connection of RHS (Rectangular hollow section) section to concrete column, RHS to RHS and detailing of joint-E and F is carried out.



All dimensions are in mm

Figure 6.17 Supporting structural system modules for braced barrel vault

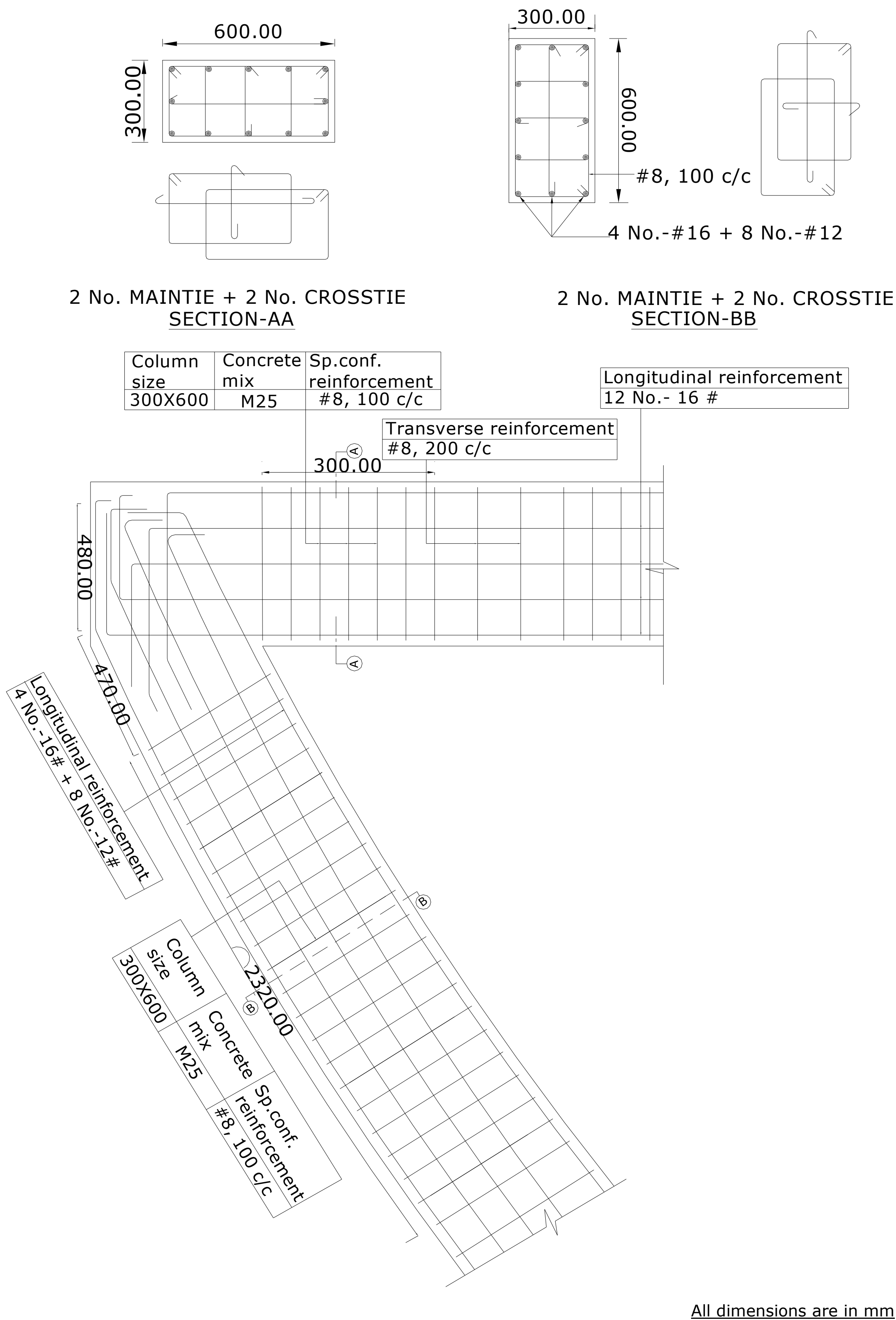
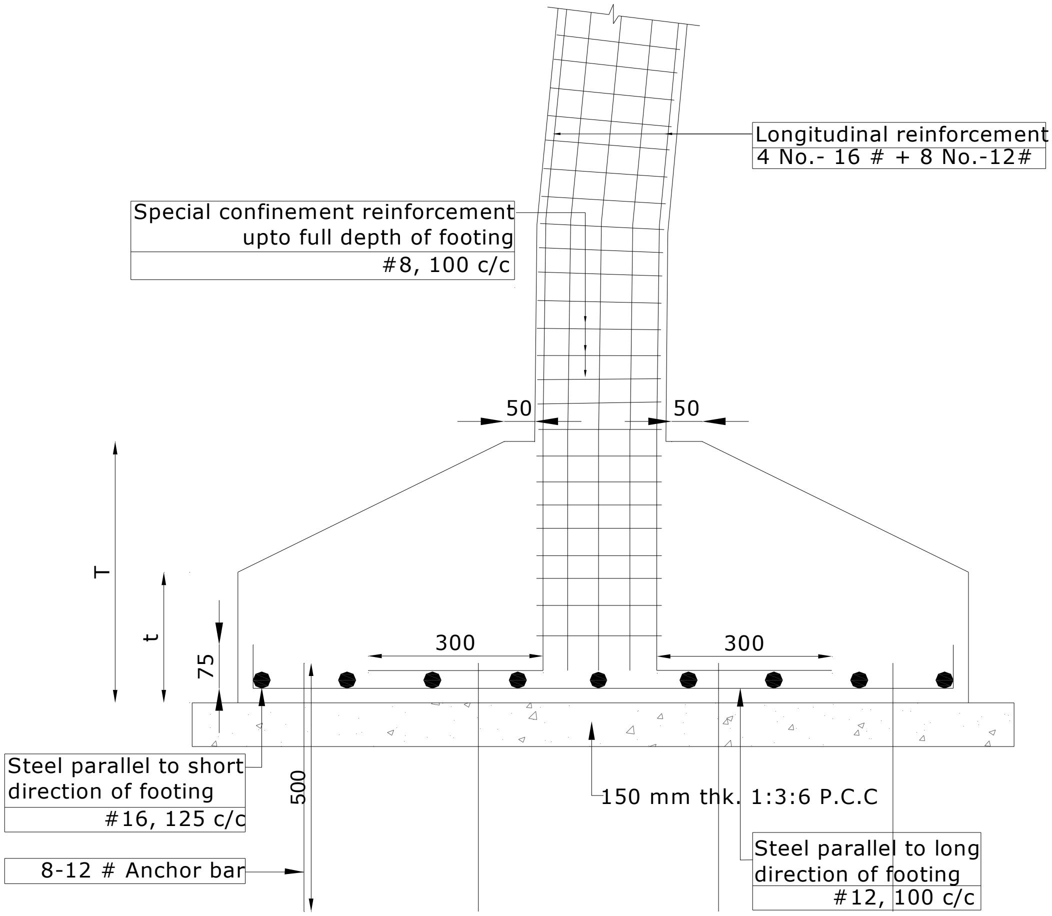
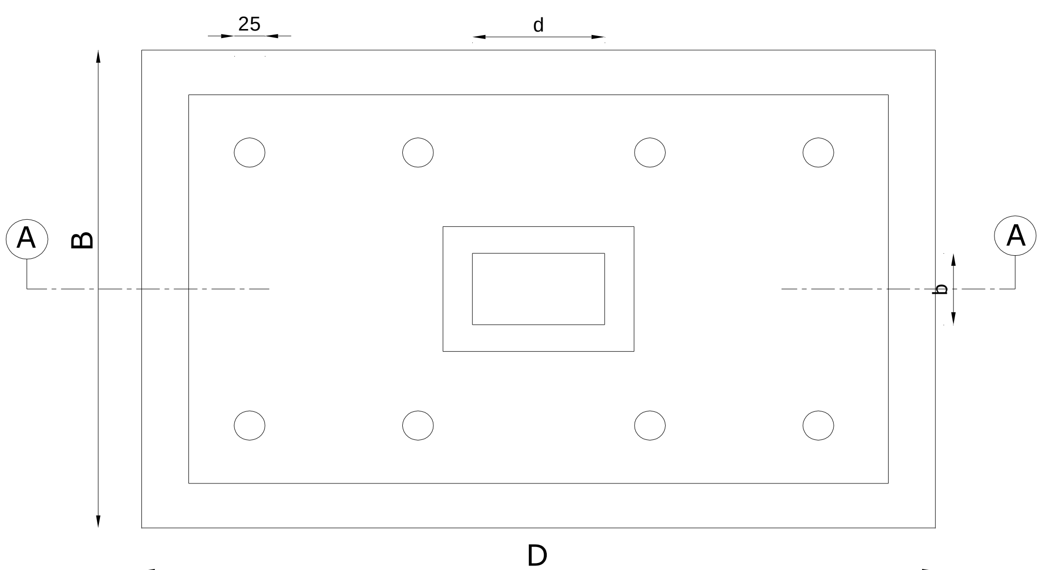


Figure 6.18 Joint-E



Section- AA



Plan

All dimensions are in mm

Figure 6.19 Joint-F

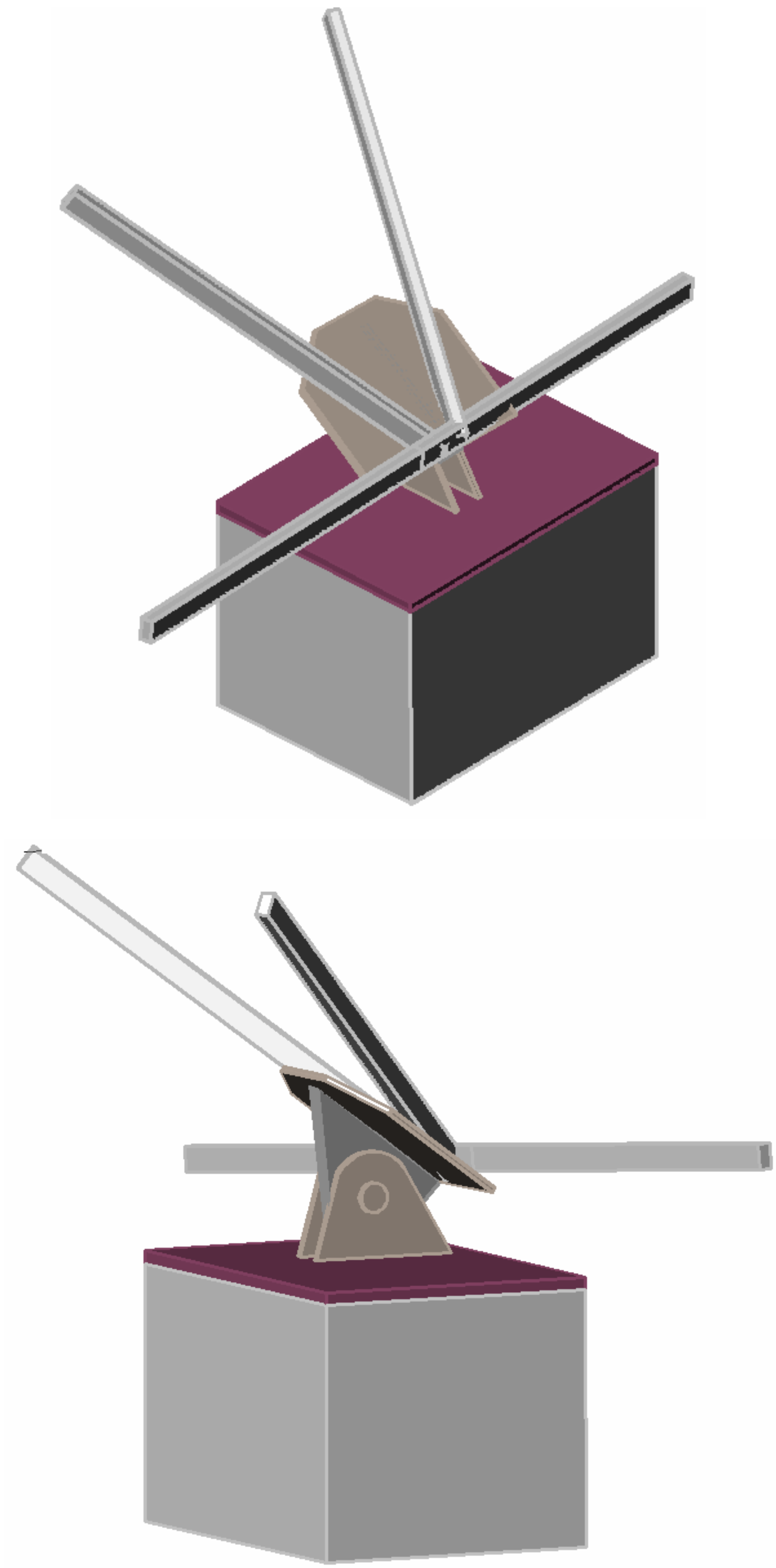
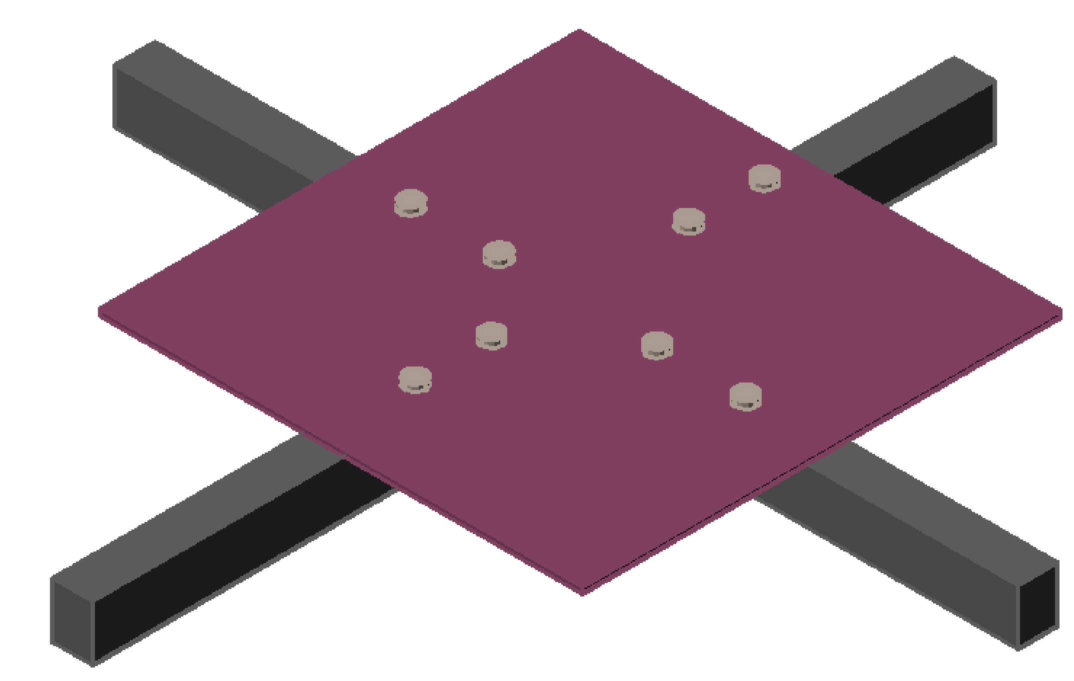
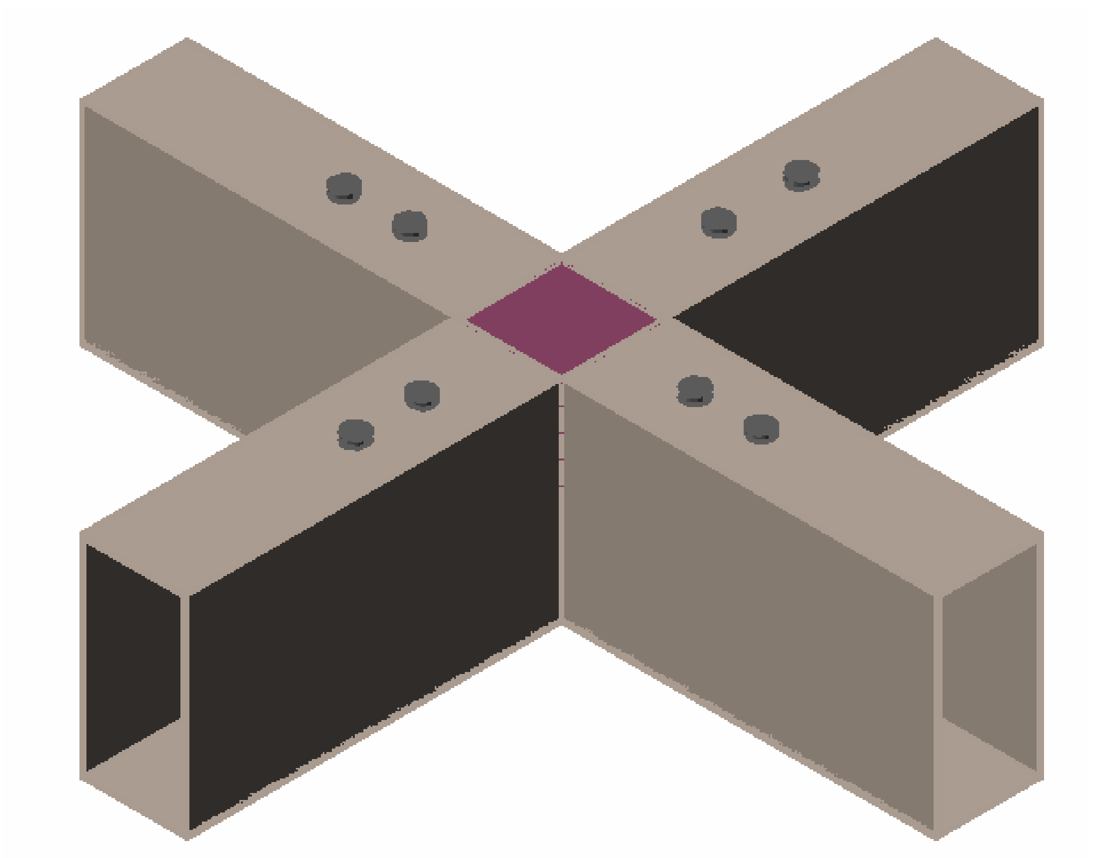


Figure 6.20 3d views of connection of RHS section to concrete column



(a) Top view



(b) Inner View

Figure 6.21 3-d views of connection of RHS section to RHS section

6.4 SUMMARY

All joints are considered as rigid joints during modeling in case of both space truss systems. Wind loads are predominant compared to Earthquake loads. As such the sections required to satisfy axial force criteria is not as much of that which are required to satisfy serviceability criteria i.e. deflection. Due to high amount of axial thrust present in braced barrel vault system at top of column, a special structural system has been developed. Special kind of connection has been developed to satisfy its structural behavior under actual condition. In some case of footing, axial forces are small and moments are more, so footing sizes are comparatively big.

7. QUANTITY ANALYSIS

7.1 GENERAL

The quantity analysis of an indoor sports stadium require familiar with current market rates for material used in construction of indoor sports stadium. In this chapter, quantity analysis of double layer cable, double layer grid and braced barrel vault is described. As such all frames are identical in all three structural systems. So quantity analysis is carried out for a panel and structural cost/unit area is found out.

7.2 DOUBLE LAYER CABLE

Double layer cable roof structure is a combination of roof made of steel cable + supporting structure made of R.C.C. Here the size of panel is= 40 m X 3 m.

Table 7.1 Quantity of double layer cable

Sr. No	Items	Quantity	Rate	Unit	Amount
1	Excavation (dense or hard soil)	20.00	49.00	Cu.M	980.00
2	Excavation (Hard murrum)	21.00	90.00	Cu.M	1890.00
3	P.C.C (1:3:6)	1.70	1695.00	Cu.M	2881.50
4	Filling in foundation	60.00	24.80	Cu.M	1488.00
5	M-200 (footing)	2.30	2301.00	Cu.M	5292.30
6	M-250 (column)	9.00	4000.00	Cu.M	36000.00
7	M-250 (beam)	8.40	4000.00	Cu.M	33600.00
8	M-200 (slab)	22.70	3500.00	Cu.M	79450.00
9	HYSD reinforcement	3142.00	35.00	Kg	109970.00
10	Structural steel cable	1824.00	58.00	Kg	105792.00
11	Structural steel tube	525.00	50.00	Kg	26250.00

Total Rs= 403593.80

Add 2% W.C= 8071.87

Total Cost Rs. = 411665.68

Say Rs. 411700.00

Rs/m^2 = 3430.83

Rs/sq.ft = 318.85

7.3 DOUBLE LAYER GRID

Double layer grid structure is a combination of roof made of structural steel tube + supporting structure made of R.C.C. Here the size of panel is = 40 m X 4 m.

Table 7.2 Quantity of double layer grid

Sr. No	Items	Quantity	Rate	Unit	Amount
1	Excavation (dense or hard soil)	34.00	49.00	Cu.M	1666.00
2	Excavation (Hard murrum)	34.00	90.00	Cu.M	3060.00
3	P.C.C (1:3:6)	3.40	1695.00	Cu.M	5763.00
4	Filling in foundation	80.00	24.80	Cu.M	1984.00
5	M-200 (footing)	6.40	2301.00	Cu.M	14726.40
6	M-250 (column)	8.70	4000.00	Cu.M	34800.00
7	M-250 (beam)	9.90	4000.00	Cu.M	39600.00
8	M-200 (slab)	29.70	3500.00	Cu.M	103950.00
9	HYSD reinforcement	4350.00	35.00	Kg	152250.00
10	Structural steel tube	11839.00	50.00	Kg	591950.00

Total Rs= 949749.40

Add 2% W.C= 18994.98

Total Cost Rs. = 968744.38

Say Rs. 969000.00

Rs/m^2 = 6056.25

Rs/sq.ft =562.84

7.4 BRACED BARREL VAULT

Double layer cable roof structure is a combination of roof made of structural RHS + supporting structure made of R.C.C. Here the size of panel is = 40 m X 4 m.

Table 7.3 Quantity of braced barrel vault

Sr. No	Items	Quantity	Rate	Unit	Amount
1	Excavation (dense or hard soil)	50.00	49.00	Cu.M	2450.00
2	Excavation (Hard murrum)	50.00	90.00	Cu.M	4500.00
3	P.C.C (1:3:6)	5.00	1695.00	Cu.M	8475.00
4	Filling in foundation	80.00	24.80	Cu.M	1984.00

5	M-200 (footing)	9.40	2301.00	Cu.M	21629.40
6	M-250 (column)	11.00	4000.00	Cu.M	44000.00
7	M-250 (beam)	9.50	4000.00	Cu.M	38000.00
8	M-200 (slab)	29.70	3500.00	Cu.M	103950.00
9	HYSD reinforcement	4584.00	35.00	Kg	160440.00
10	Structural steel tube	8129.00	50.00	Kg	406450.00

Total Rs= 791878.40

Add 2% W.C= 15837.57

Total Cost Rs. = 807715.97

Say Rs. 807800.00

Rs/m^2 = 5048.75

Rs/sq.ft =469.21

7.5 SUMMARY

After carry out quantity analysis, it has been found that the structural cost/ sq.ft for double layer cable, double layer grid and braced barrel vault are found 320.00, 563.00 and 470.00 respectively.

8. SUMMARY AND FUTURE SCOPE OF WORK

8.1 PRILIMINARY REMARKS

Indoor sport stadium comes under the category of large span structure. Therefore a parametric study is carried out to study the variation of forces in three types of space structural systems namely cable suspended roof structure (single layer and double layer), double layer grid (square on square offset-cornice type) and braced barrel vault (lamella type).

In present work an attempt has been made to study different aspects of space structural systems analytically. Based on the results obtained through analytical work, conclusions are drawn and presented in the following sections. Finally, guidelines for future work have also been discussed.

8.2 MAJOR OBSERVATIONS AND CONCLUSIONS

Based on the study carried out on different space structural systems following conclusions are drawn:

8.2.1Modeling:

Beam made up of small straight element and cable made of small straight element gives good results for single cable and double cable suspended roof structure respectively. During modeling of double layer grid and braced barrel vault all elements are defined as beam members. In STAAD-Pro area load on curved surface does not give appropriate results. So area load is converted into member load which gives proper results.

8.2.2 Analysis, Design and Detailing:

For the same amount of loading, double curved cable structure gives twice amount of axial force in the cable compared to single cable structure. In case of single layer cable suspended structure high amount of deflection is found out for less dia of cable. To get permissible value of deflection use of 100 mm size of cable is essential.

Anchor bars are the best option to resist lateral forces which are produced because of the axial thrust in the cable structure. When anchor bars provided at 45^0 then moments in the structure is 10 times less then the structure without anchor bars.

Seating gallery beams are subjected to large forces compared to any other structural component of indoor sports stadium. All columns and isolated footings are subjected to axial compression + bending. Sitting gallery inclined beams are subjected to high amount of axial compression + bending while plinth beams are subjected to axial tension + bending. Sitting gallery inclined beam is designed as a column subjected to axial compression + bending, while plinth beam as a member subjected to axial tension + bending. All roof members are either in axial compression or tension. Moments in the members are negligible. To satisfy serviceability criteria, sections in case of space trusses roof structure are more than its capacity of axial compression and tension. Tube sections are not compatible for very long curved shape due to its connection problems. So RHS section has been adopted in design of members.

8.2.3 Quantity

Structural cost/sq.ft for double layer cable structure, double layer grid and braced barrel vault is 320.00, 563.00, and 470.00 respectively. So double layer cable structure is most economical structural system to cover area of 40 m X 60 m.

8.3 RECOMMENDETIONS FOR FUTURE WORK

8.3.1 Analytical

- Analysis and design of indoor sports stadium using retractable roof.
- Adopt different configurations of double layer grid and braced barrel vault and carry out parametric study to find the most economical configurations for a particular span.
- Use of double layer grid for multi-storey building.
- To cover span about 100 m and more than that try with triple layer grid system.
- Use of braced dome, Tensegritic structure, stressed skin systems, folded plate roof structure, Tension membrane structures etc. as different

structural alternative of space structural configurations to cover large span column free area.

8.3.2 Experimental

- Study on behavior of tubular space trusses with simple and reinforced end- flattened nodes.
- Study of behavior of composite space trusses.

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APPENDIX-A

A.1 GENERAL:

In this section analysis of structures are discussed. The main loads are considered are Dead load, Live load, Wind load and Earthquake load. Different loads are considered as per Indian standard as follows:

a) Dead load as per IS: 875-(Part-I)-1987.

b) Live load as per IS: 875-(Part-II)-1987.

c) Wind load as per IS: 875-(Part-III)-1987.

d) Earthquake load as per IS: 1893-(Part-I)-2002.

In IS: 875-(part-III)-1987 there is not any table regarding external pressure coefficients for singly curved cable roof structure. So use the external pressure coefficients of flat roof as per Table-4 and Table-5. While for double curved cable roof structure use the external pressure coefficients of curved roof as per Table-15.

As Dynamic wind analysis is because of the external force only. So that internal pressure coefficients are neglected and only external pressure coefficients are considered in the analysis.

In Appendix the calculation of loads for all three space structural systems are as follows:

❖ **SINGLY CURVED CABLE ROOF STRUCTURE:**

1) Static wind analysis (As per IS: 875-(Part-III)-1987)

2) Dynamic wind analysis (As per IS: 875-(Part-III)-1987)

3) Static seismic analysis (As per IS: 1893-(Part-I)-2002)

❖ **DOUBLY CURVED CABLE ROOF STRUCTURE:**

1) Static wind analysis (As per IS: 875-(Part-III)-1987)

2) Dynamic wind analysis (As per IS: 875-(Part-III)-1987)

3) Static seismic analysis (As per IS: 1893-(Part-I)-2002)

Here in case of double layer grid and braced barrel vault wind forces are same as that of the single curved cable structure and double curved cable structure respectively. So in case of double layer grid and braced barrel vault only static seismic calculations are shown.

❖ **DOUBLE LAYER GRID STRUCTURE:**

1) Static seismic analysis (As per IS: 1893-(Part-I)-2002)

❖ **BRACED BARREL VAULT STRUCTURE:**

1) Static seismic analysis (As per IS: 1893-(Part-I)-2002)

Some other excel sheets regarding calculations of,

(1) Tension and compression member.

(2) Column subjected to axial force + uniaxial moment.

(3) Isolated footing subjected to axial force + uniaxial moment.

is also mentioned.

Wind forces on a rectangular singly curved cable shape building (AS PER IS-875(PART-3)-1987-STATIC METHOD)

Data given:

Location of project:	Rajkot	
width of structure, w:	40	m
length of structure, L:	60	m
Height of structure, H:	15	m

Wind Data:

1. wind zone:	II		
Basic wind speed, Vb:	39	m/s.	(sec-5.2)
2. Terrain category:	2		(sec-5.3.2.1)

Design factors:

Risk coefficient factor k1:	1		(Table-1)
Terrain & height factor k2:	0.97		(Table-2)
Topography factor k3:	1		(sec-5.3.3.1)
The building is of medium permeability.			
Design wind speed, Vz=Vb*k1*k2*k3	37.8	m/s	(sec-5.4)
Design wind pressure, $Pz=0.6*Vz^2$	859	N/m^2	(sec-6.2.1)

Wind load calculations:

Internal pressure coefficients, Cpi 0.5 -0.5 (sec-6.2.3.2)

Building shall be analyzed once for pressure of 0.5 from inside and then for a suction of -0.5 from inside along with external pressure coefficient.

External pressure coefficients Cpe:

On Roof: Using the table 5 with roof angle 0 without local coefficients. For h/w=0.375, pressure coefficients are tabulated below:

Portion of roof	Wind incidence Angle		
	0	90	(Table-5)
E	-0.8	-0.8	
F	-0.8	-0.4	
G	-0.4	-0.8	
H	-0.4	-0.4	

For 0 wind incidence, for E/G	-0.3	0.1	-1.3
(end zone)	-1.3	-0.9	0.1

For 90 wind incidence, for E/G	-0.3	-0.3	-1.3		
(end zone)	-1.3	-1.3	-0.3	-1.3	Suction
				0.1	Pressure
For 0 wind incidence, for F/H	-0.3	0.1	-1.3		
(end zone)	-1.3	-0.9	0.1		
For 90 wind incidence, for F/H	0.1	0.1	-0.9		
(end zone)	-0.9	-0.9	0.1		

Design pressure Coefficients for walls=

For h/w= 0.375

L/w= 1.50

C_{pe} for walls,

Angle of incidence	0	90	
Wall-A	0.7	-0.5	(Table-4)
Wall-B	-0.25	-0.5	
Wall-C	-0.6	0.7	
Wall-D	-0.6	-0.1	

These will be combined with internal pressure coefficients as earlier, equal to C_{pi}=0.5

C_{pnet} for long walls A and B	1.20	0.20	0.00	-1.00	**1.2**	Pressure
C_{pnet} for long walls A and B	0.25	-0.75	0.00	-1.00	**-1.0**	Suction
C_{pnet} for short walls C and D	-0.10	-1.10	1.20	0.20	**1.2**	Pressure
C_{pnet} for short walls C and D	-0.10	-1.10	0.40	-0.60	**-1.1**	Suction

Design pressures for walls:

For long walls:

F=C_{pnet} X P_d	1.03	kN/m^2	Pressure
	-0.86	kN/m^2	Suction

For short walls:

F=C_{pnet} X P_d	1.03	kN/m^2	Pressure
	-0.94	kN/m^2	Suction

For Roof:

F=C_{pnet} X P_d	-1.12	kN/m^2	Suction
	0.086	kN/m^2	Pressure

Wind forces on a rectangular singly curved cable shape building
(AS PER IS 875-(PART-3)-1987)
(DYNAMIC WIND ANALYSIS)-GUST FACTOR METHOD

Data given:

Location of project:	Rajkot	
width of structure, w:	40	m
length of structure, L:	60	m
Height of structure, H:	15	m

Wind Data:

1. wind zone:	II		
Basic wind speed, Vb:	39	m/s.	(sec-5.2)
2. Terrain category:	2		(sec-5.3.2.1)

Design factors:

Risk coefficient factor k1:	1		(sec-5.3.1, Table-1)
Terrain & height factor k2:	0.72		(sec-5.3.2.2, Table-33)
Topography factor k3:	1		(sec-5.3.3.1)
Design wind speed,	28.08	m/s	(sec-5.4)
Design wind pressure,	473.1	N/m^2	(sec-6.2.1)

Wind load calculations:

Internal pressure coefficients Cpi= 0 0 (sec-6.2.3.2)

As such gust factor is only due to external pressure, internal pressure coefficients should be taken as 0.

On Roof: Using the table 5 with roof angle 0 without local coefficients. For h/w=0.375, pressure coefficients are tabulated below:

Portion of roof	Wind incidence Angle		
	0	90	(Table-5)
E	-0.8	-0.8	
F	-0.8	-0.4	
G	-0.4	-0.8	
H	-0.4	-0.4	

For 0 wind incidence, for E/G	-0.8	-0.4	-0.8		
(end zone)	-0.8	-0.4	-0.4		
For 90 wind incidence, for E/G	-0.8	-0.8	-0.8		
(end zone)	-0.8	-0.8	-0.8	-0.8	Suction
For 0 wind incidence, for F/H (end	-0.8	-0.4	-0.8		
zone)	-0.8	-0.4	-0.4		

For 90 wind incidence, for F/H	-0.4	-0.4	-0.4
(end zone)	-0.4	-0.4	-0.4

Design pressure Coefficients for walls:

For h/w= 0.38

L/w= 1.50

C_{pe} for walls,

Angle of incidence	0	90	
Wall-A	0.70	-0.50	(Table-4)
Wall-B	-0.25	-0.50	
Wall-C	-0.60	0.70	
Wall-D	-0.60	-0.10	

These will be combined with internal pressure coefficients as earlier, equal to C_{pi}=0.5

C_{pnet} for walls A and B	0.7	0.7	-0.5	-0.5	0.7	Pressure
C_{pnet} for walls A and B	-0.3	-0.3	-0.5	-0.5	-0.5	Suction
C_{pnet} for walls C and D	-0.6	-0.6	0.7	0.7	0.7	Pressure
C_{pnet} for walls C and D	-0.6	-0.6	-0.1	-0.1	-0.6	Suction

G = Gust factor = (peak load/mean load)

$$G = 1 + g_t r \sqrt{[B(1+\Phi)^2} + \frac{SE}{\beta}$$

Case-1: when wind is on shorter side

T:	0.174 Sec	
Fo:	5.738 Hz	
C_y:	10	
C_z:	12	
λ=(Cy*b)/(Cz*h)	2.222	
Fo=Cz*fo*h/ Vz	36.78	
From fig-8		
g_f*r:	1.375	
L(h):	1000	
C_z*h/L(h)	0.18	
fo*L(h)/V_h	204.3	
From fig-9		
Background factor, B:	0.75	
From fig-10		
S:	0.004	
Φ:	0	(clause-8.3)
E:	0.012	(fig-11)
β:	0.016	(Table-34)

1+Φ:	1		
B(1+Φ)^2:	0.75		
SE/β:	0.003		
GUST FACTOR G=	**2.193**		

Case-2: when wind is on longer side

T:	0.213	Sec	
fo:	4.685	Hz	
C_y:	10		
C_z:	12		
λ=(Cy*b)/(Cz*h)	3.333		
Fo=Cz*fo*h/ Vz	30.03		
From fig-8			
g_f*r:	1.375		
L(h):	1000		
C_z*h/L(h)	0.18		
fo*L(h)/V_h	166.8		
From fig-9			
Background factor, B:	0.73		
From fig-10			
S:	0.004		
Φ:	0		(clause-8.3)
E:	0.015		(fig-11)
β:	0.016		(Table-34)
1+Φ:	1		
B(1+Φ)^2:	0.73		
SE/β:	0.003		
GUST FACTOR G=	**2.178**		

Design pressures for walls:

For long walls:

F=C_{pnet} X P_d X G	0.72	kN/m^2	Pressure
	-0.52	kN/m^2	Suction

For short walls:

F=C_{pnet} X P_d X G	0.73	kN/m^2	Pressure
	-0.62	kN/m^2	Suction

For Roof:

F=C_{pnet} X P_d X G	-0.83	kN/m^2	Suction

Earthquake forces on a rectangular singly curved cable shape building

(As per IS:1893-2002 (Part-I))- STATIC METHOD

Data given:

Location Of Project:	Rajkot	
Width Of Structure, W:	40	m
Length Of Structure, L:	60	m
Height Of Structure, H:	18	m
Number Of Division In Length Direction:	20	
Width Of Column, C1:	0.30	m
Depth Of Column, C1:	0.60	m
Width Of Column, C2:	0.30	m
Depth Of Column, C2:	0.60	m
Length Of Column, C2:	5.50	m
Width Of Beam, B1:	0.30	m
Depth Of Beam, B2:	0.60	m
Length Of Beam, B2:	7.63	m
Width Of Slab, S1:	3.00	m
Length Of Slab, S1:	7.63	m
Thickness Of Slab, S1:	0.10	m
Density Of Concrete:	25	kN/m^3
Live Load Considered :	0.75	kN/m^2
Soil Strata:	Hard soil	

Earthquake Data:

earthquake zone:	III
Zone factor:	0.16
Importance factor I:	1.5
R:	3

Calculate the dead load :

weight of cladding & self weight of cable:	1	kN/m
	840	kN
Weight of column, C1:	3402	kN
Weight of column, C2:	1040	kN
Weight of beam, B1:	1442	kN
Weight of slab, S1:	2289	kN
	9013	kN

Calculate the live load :

LL on floor= 450 kN

As per IS 1893-2002 LL on roof is not countable.

Calculate the Base shear :

Base shear, $V_b = A_h W$

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

Estimation of Base shear:

For X-direction

T_x= 0.26 sec

For Y-direction

T_y= 0.21 sec

Sa/g in X-direction : 2.5

Sa/g in Y-direction : 2.5

Ah in X-direction : 0.100

Ah in Y-direction : 0.100

Results :

Floor	height (m)	Weight w (kN)	wh^2	Lateral force in X-direction	Lateral force in Z-direction.
Roof	18	1701	551124.0	546.25	546.25
At 6.5 m from ground	6.5	6471.6	273423.8	271.01	271.01
Ground	0	0	0	0	0
		8172.6	824547.8		

Base shear V_b in X-direction : 817 kN

Base shear V_b in Y-direction : 817 kN

Distribution of Base shear:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Qi= 546 kN

Wind forces on a rectangular double curved cable shape building (AS PER IS-875(PART-3)-1987-STATIC METHOD)

Data given:

Location of project :	Rajkot	
width of structure, w :	40	m
length of structure, L :	60	m
Height of structure, H :	15	m

Wind Data:

1. wind zone:	II		
Basic wind speed, Vb=	39	m/s.	(sec-5.2)
2. Terrain category:	2		(sec-5.3.2.1)

Design factors:

Risk coefficient factor k1:	1		(Table-1)
Terrain & height factor k2:	0.97		(Table-2)
Topography factor k3:	1		(sec-5.3.3.1)

The building is of Medium Permeability.

Design wind speed, Vz= Vb*k1*k2*k3	37.8	m/s	(sec-5.4)
Design wind pressure, Pz=0.6*Vz^2	859	N/m^2	(sec-6.2.1)

Wind load calculations:

Internal pressure coefficients Cpi= 0.5 -0.5 (sec-6.2.3.2)

Building shall be analyzed once for pressure of 0.5 from inside and then for a suction of -0.5 from inside along with external pressure coefficient.

External pressure coefficients Cpe

On Roof: Using the table 15, for H/l=0.1 pressure coefficients are tabulated below:

Value of c and c_2	-0.8	-0.8
	-1.3	-1.3
	-0.3	-0.3
	-1.3	Suction

Design pressure Coefficients for walls=

C_{pe} for walls,

For wind ward side: 0.8

For leeward side:	-0.6			
	0.3	-1.1	0.3	Pressure
	-1.3	-0.1	-1.3	Suction

Design pressures for walls:

For long wall-A (windward side):

F=C_{pnet} X P_d	0.26	kN/m^2	Pressure
	-1.12	kN/m^2	Suction

For long wall-B (Leeward side):

F=C_{pnet} X P_d	-0.94	kN/m^2	Suction
	-0.09	kN/m^2	Suction

For Roof:

F=C_{pnet} X P_d	-1.12	kN/m^2	Suction

Wind forces on a rectangular doubly curved cable shape building (AS PER IS 875-(PART-III)-1987) (DYNAMIC WIND ANALYSIS)-GUST FACTOR METHOD

Data given:

Location of project:	Rajkot	
width of structure, w:	40	m
length of structure, L:	60	m
Height of structure, H:	15	m

Wind Data:

1. wind zone:	II		
Basic wind speed, Vb=	39	m/s	(sec-5.2)
2. Terrain category:	2		(sec-5.3.2.1)

Design factors:

Risk coefficient factor k1:	1		(sec-5.3.1, Table-1)
terrain & height factor k2:	0.72		(sec-5.3.2.2, Table-33)
topography factor k3:	1		(sec-5.3.3.1)
The building is of Medium Permeability.			
Design wind speed, Vz=Vb*k1*k2*k3	28.08	m/s	(sec-5.4)
Design wind pressure, Pz=0.6*Vz^2	473.1	N/m^2	(sec-6.2.1)

Wind load calculations:

Internal pressure coefficients Cpi=	0	0	(sec-6.2.3.2)

As such gust factor is only due to external pressure, internal pressure coefficients should be taken as 0.

External pressure coefficients Cpe=

On Roof: Using the table 15, For H/l=0.1, pressure coefficients are tabulated below:

Value of c and c_2	-0.8	-0.8
	-0.8	Suction

Design pressure Coefficients for walls=

C_{pe} for walls,

For wind ward side:	0.8		
For leeward side:	-0.6		
	0.8	-0.6	0.8
	0.8	-0.6	-0.6

G = Gust factor = (peak load/mean load)

$$G = 1 + g_t r\sqrt{[B(1+\Phi)^2} + \frac{SE}{\beta}$$

Case-1: when wind is on smaller side

T:	0.174	Sec	
fo:	5.738	Hz	
C_y:	10		
C_z:	12		
λ=(Cy*b)/(Cz*h)	2.222		
Fo=Cz*fo*h/ Vz	36.78		
From fig-8			
g_f*r:	1.375		
L(h):	1000		
C_z*h/L(h)	0.18		
fo*L(h)/V_h	204.3		
From fig-9			
Background factor, B:	0.75		
From fig-10			
S:	0.004		
Φ:	0		(clause-8.3)
E:	0.012		(fig-11)

β:	0.016		(Table-34)
1+Φ:	1		
B(1+Φ)^2:	0.75		
SE/β:	0.003		
GUST FACTOR G=	**2.193**		

Case-2: when wind is on longer side

T:	0.213	Sec	
fo:	4.685	Hz	
C_y:	10		
C_z:	12		
λ=(Cy*b)/(Cz*h)	3.333		
Fo=Cz*fo*h/ Vz	30.03		
From fig-8			
g_f*r:	1.375		
L(h):	1000		
C_z*h/L(h)	0.18		
fo*L(h)/V_h	166.8		
From fig-9			
Background factor, B=	0.73		
From fig-10			
S:	0.004		
Φ:	0		(clause-8.3)
E:	0.015		(fig-11)
β:	0.016		(Table-34)
1+Φ:	1		
B(1+Φ)^2:	0.73		
SE/β:	0.003		
GUST FACTOR G=	**2.178**		

Design pressures for walls:

For long walls (windward side):

F=C_{pnet} X P_d X G	0.82	kN/m^2	Pressure

For long walls (Leeward side):

F=C_{pnet} X P_d X G	-0.62	kN/m^2	Suction

For Roof:

F=C_{pnet} X P_d X G	-0.83	kN/m^2	Suction

Earthquake forces on a rectangular doubly curved cable shape building

(As per IS:1893-2002 (Part-I))- STATIC METHOD

Data given:

Location Of Project:	Rajkot	
Width Of Structure, W:	40	m
Length Of Structure, L:	60	m
Height Of Structure, H:	18	m
Number Of Division In Length Direction:	20	
Width Of Column, C1:	0.30	m
Depth Of Column, C1:	0.60	m
Width Of Column, C2:	0.30	m
Depth Of Column, C2:	0.60	m
Length Of Column, C2:	5.50	m
Width Of Beam, B1:	0.30	m
Depth Of Beam, B2:	0.60	m
Length Of Beam, B2:	7.63	m
Width Of Slab, S1:	3.00	m
Length Of Slab, S1:	7.63	m
Thickness Of Slab, S1:	0.10	m
Density Of Concrete:	25	kN/m^3
Live Load Considered :	0.75	kN/m^2
Soil Strata:	Hard soil	

Earthquake Data:

earthquake zone:	III
Zone factor=	0.16
Importance factor I=	1.5
R=	3

Calculate the dead load :

weight of cladding & self weight of cable=	1	kN/m
	840	kN
Weight of column, C1=	3402	kN
Weight of column, C2=	1040	kN
Weight of beam, B1=	1442	kN
Weight of slab, S1=	2289	kN
	9013	kN

calculate the live load :

LL on floor= 450 kN

As per IS 1893-2002 LL on roof is not countable.

calculate the Base shear :

Base shear, $V_b = A_h W$

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

Estimation of Base shear:

For X-direction

T_x= 0.26 sec

For Y-direction

T_y= 0.21 sec

Sa/g in X-direction= 2.5

Sa/g in Y-direction= 2.5

Ah in X-direction= 0.100

Ah in Y-direction= 0.100

Results :

Floor	height (m)	Weight w (kN)	wh^2	Lateral force in X-direction.	Lateral force in Z-direction.
Roof	18	1701	551124.0	546.25	546.25
At 6.5 m from ground	6.5	6471.6	273423.8	271.01	271.01
Ground	0	0	0	0	0
		8172.6	824547.8		

Base shear V_b in X-direction= 817 kN

Base shear V_b in Y-direction= 817 kN

Distribution of Base shear:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Qi= 546 kN

Earthquake forces on a rectangular Double layer grid
(As per IS:1893-2002 (Part-I))- STATIC METHOD

Data given:

Location Of Project:	Rajkot	
Width Of Structure, W:	40	m
Length Of Structure, L:	60	m
Height Of Structure, H:	18	m
Number Of Division In Length Direction:	15	
Width Of Column, C1:	0.30	m
Depth Of Column, C1:	0.60	m
Width Of Column, C2:	0.30	m
Depth Of Column, C2:	0.60	m
Length Of Column, C2:	5.50	m
Width Of Beam, B1:	0.30	m
Depth Of Beam, B2:	0.60	m
Length Of Beam, B2:	7.63	m
Width Of Slab, S1:	3.00	m
Length Of Slab, S1:	7.63	m
Thickness Of Slab, S1:	0.10	m
Density Of Concrete:	25	kN/m^3
Live Load Considered :	0.75	kN/m^2
Soil Strata:	Hard soil	

Earthquake Data:

earthquake zone:	III
Zone factor=	0.16
Importance factor I=	1.5
R=	3

Weight of cladding & self weight of cable=	1	kN/m
	640	kN
Weight of column, C1=	2592	kN
Weight of column, C2=	792	kN
Weight of beam, B1=	1099	kN
Weight of slab, S1=	1717	kN
	6839	kN

Calculate the live load :

LL on floor= 450 kN

As per IS 1893-2002 LL on roof is not countable.

Calculate the Base shear :

Base shear, $V_b = A_h W$

$$A_h = \frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

Estimation of Base shear:

For X-direction

T_x= 0.26 sec

For Y-direction

T_y= 0.21 sec

Sa/g in X-direction= 2.5

Sa/g in Y-direction= 2.5

Ah in X-direction= 0.100

Ah in Y-direction= 0.100

Results :

Floor	height (m)	Weight w (kN)	wh^2	Lateral force in X-direction.	Lateral force in Z-direction.
Roof	18	1296	419904.0	415.13	415.13
At 6.5 m from ground	6.5	4903.5	207171.6	204.82	204.82
Ground	0	0	0	0	0
		6199.5	627075.6		

Base shear V_b in X-direction= 620 kN

Base shear V_b in Y-direction= 620 kN

Distribution of Base shear:

$$Q_i = V_B \frac{W_i h_i^2}{\sum_{j=1}^{n} W_j h_j^2}$$

Qi= 415 kN

DESIGN OF UNIAXIAL SLENDER COLUMN (SP:16)

Data Given:

Height Of Column:		2.0	m
Width Of Column:		0.30	m
Depth Of Column:		0.60	m
Concrete Grade:	M	25	
Characteristic Strength Of Reinforcement:		415	N/mm^2
Factored Load:		393.61	kN
Factored Moment:		283.20	kNm

Assuming	16	mm bars with	40	mm covers

d'=	48	mm
d'/D=	0.08	
charts for d'/D=0.10 will be use		
Pu/(fck*b*d)=	0.0875	
$Mu/(fck*b*d^2)$	0.1049	

From chart 45,

P/fck=	0.06
p=	1.5
Ast=	2700
No. of bars=	13.436

Provide 8 no. of 16 mm + 4-20 mm

DESIGN OF TENSION MEMBER

Data Given:

Axial force:	588	kN
Length of member:	2	m
Permissible axial stress in tension:	190	Mpa
Grade of steel:	Yst 32	Mpa
Area required:	3094.74	mm^2
	30.95	cm^2

Trial 1:

Try Heavy steel tube of 150 mm nominal dia having following properties:

Properties:

Nominal bore :	150	mm
Outside diameter:	168.3	mm
Class:	Heavy 2	

Thickness:	6.3	mm	
Weight:	25.20	kg/m	
Area of cross section, a:	32.00	cm^2	
Moment of Inertia , $I_{xx=}$ I_{yy}	1053.00	cm^4	
Modulus of section, Z_{xx} = Z_{yy}	125.00	cm^3	
Radius of Gyration, $r_{xx=}$ r_{yy}	5.73	cm	
λ=(l / r_{yy})	34.90	<	350
	O.K		
P =	608.00	>	588
	O.K		

So use Heavy steel tube of 150 mm nominal dia.

DESIGN OF COMPRESSION MEMBER

Data Given:	102.79	kN
Length of member:	2.00	m
Top condition of member:	Fixed	
Bottom condition of member:	Fixed	
Permissible axial compression stress:	160	Mpa
Grade of steel:	320	Mpa
Effective length:	1.3	m
Area required:	642.44	mm^2
	6.42	cm^2

Trial 1:

Try Heavy steel tube of 50 mm nominal dia having following properties:

Properties:

Nominal bore:	50	mm	
Outside diameter:	60.3	mm	
Class:	Heavy		
Thickness:	4.5	mm	
Weight:	6.19	kg/m	
Area of cross section, a:	7.88	cm^2	
Moment of Inertia , $I_{xx=}$ I_{yy}	30.90	cm^4	
Modulus of section, Z_{xx} = Z_{yy}	10.20	cm^3	
Radius of Gyration, $r_{xx=}$ r_{yy}	1.98	cm	
λ = l / r_{yy}	65.66	<	180

	O.K		
Бас:	142.15	Mpa	
P =	112.01	>	102.8
	O.K		

So use Heavy steel tube of 50 mm nominal dia.

DESIGN OF ISOLATED FOOTING SUBJECTED TO UNIAXIAL MOMENT

DATA GIVEN:

Width of column:			300	mm
Length of column:			600	mm
Service column load :			573.3	kN
moment:			156.4	kNm
Grade of concrete:		M:	20	
SBC:			350	kN/m^2
Grade of steel:		Fe:	415	
Concrete Cover:			50	mm
No. of bars:	12	No.	16	mm

Size of footing:

Column load:	573.3	kN
Assume footing load:	57.33	kN
Total load:	630.7	kN
Area of footing required:	1.802	m^2
Width of footing:	1.52	m
Length of footing:	1.82	m
Area of footing provided:	2.766	m^2

Trial	B X L (m)		A (m^2)	Z (m^3)	P/A kN/m^2	M/Z kN/m^2	P max kN/m^2	P min kN/m^2
1	1.7	2.5	4.25	1.77	148.39	88.3	236.7	60.1
2	1.7	2.6	4.42	1.92	142.68	81.6	224.3	61.05
3	1.67	2.0	3.31	1.09	190.73	143	334	47.44

Adopt 1.67 m X 1.98 m size.

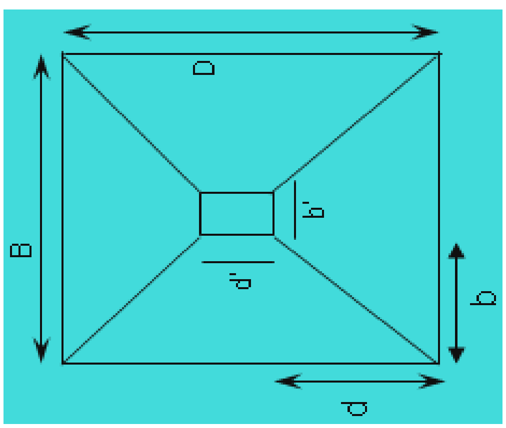
Net upward pressures:

Net upward pressure for footing design:	P max:	316.7	kN/m^2
	P min:	30.1	kN/m^2

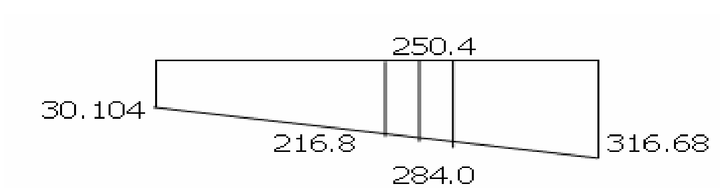
(b) Transfer of load at the base of column :

A2 :		0.18	m^2	
A1 : Smaller of	(i)	3.307	m^2	
	(ii)	5.295	m^2	
		3.307	m^2	
$\sqrt{(A1/A2)}$		4.286	>	2
$\sqrt{(A1/A2)}$		2		
Permissible bearing pressure :		10	N/mm^2	
Actual bearing pressure :		11.87	N/mm^2	
Load to be transferred by dowels :		336.8	kN	
Area of reinforcement required :		1082	m^2	
Column reinforcement :		2412	mm^2	

Use 8-25 mm # (3925 mm^2) as dowel bars. The dowels will travel up to development length of dowel bars in footing and up to development length of column bars in column. Column bars 8-25 # may be started at 75 mm from the top of the footing which are lapped with the dowels. Note that diameter of dowel bars cannot be more than 3 mm than that of column bars.



B	=	1.67	m
D	=	1.98	m
b	=	0.69	m
d	=	0.69	m
b'	=	0.3	m
d'	=	0.60	m



Moment calculations:

Mxx:	67.46	kNm
Muxx:	101.19	kNm
Myy :	80.55	kNm
Muyy:	120.82	kNm

Moment steel:

Width of resisting section :		450.00	mm	
Depth required for flexure:		148.17	mm	
Try an overall depth:		520	mm	
Assuming dia of bar :		12	mm	
dx:		464	mm	
dy:		452	mm	
dave:		458	mm	

Adopt depth 230 mm at the edge of footing.

For Mu,xx:-Steel parallel to longer direction

Mu/bd^2:		0.281		
pt:	0.12	<		0.205
pt:		0.205		
Ast :		1589	mm^2	
Minimum steel required:		1042	mm^2	
Ast required:		1589	mm^2	
No. of bars:		14.05		

Provide 15 No of 12 mm bars.

Provided steel:		1696	mm^2	
Clear distance between bars:	121	<		180
				0.K

Provide 12 mm-# @ 115 mm c/c.

For Mu,yy:-Steel parallel to shorter direction

Mu/bd^2:		0.299		
pt:	0.09	<		0.205
pt:		0.205		
Ast:		1835	mm^2	
Minimum steel required:		1042.1	mm^2	
β:		1.186		
2/(β+1):		0.915		
Reinforcement in central band of 1.67 m width		1678.8	mm^2	
Spacing of 16 mm diameter bar		120.34	mm	

No. of bars required = 13.88

To satisfy minimum steel requirement no. of bars = 9.22

One-way shear:

About x1-x1:	113.35	kN
Vu:	170.02	kN
Tv:	0.219	N/mm^2
pt:	0.22	
Tc:	0.33	N/mm^2
	O.K	

Two-way shear:

Average depth:	458	mm	
βc:	0.843		
ks:	1.343	$\ngtr$	1.0
ks:	1.0		
$\tau c = 0.25\sqrt{fck}$	1.118	N/mm^2	
Design shear strength: ks*τc	1.118	N/mm^2	

Two-way shear along line AB	158.04	kN	
Vu:	237.1	kN	
τv:	0.669	N/mm^2	
	<	1.11	N/m
		o.k.	

Length of dowel bar :

Anchoring of dowel bars in footing: D+450=		970	mm
	(ii)	624	mm
	Consider	1000	mm

Weight:

W =	42.99	kN
	<	57.3 kN
	o.k.	

APPENDIX-B

Following are some useful websites:

http://www.nicee.org

http://www.sciencedirect.com

http://www.csiberkeley.com

http://www.lightweightstructures.com

http://www.tensiledesigns.com

http://www.skyspan.com

http://www.worldstadiums.com

http://www.worldstadium.com

http://www.asce.org

http://www.reiworld.com

http://www.tensilestructures.com

http://www.zju.edu

http://www.pbs.org

http://www.geigerengineers.com

http://www.columbia.edu