Design of Members and Connectors in Opposite Edge-Supported Large Multilayered Grid Structures under Gravity and Wind Loads for High-Rise Infrastructure Safety and Structural Health Optimization

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ABSTRACT

Multi-layer grid systems are three-dimensional pin-jointed structures, which are generally used for covering roofs having large spans. The multi-layer grid structures are quite popular because of optimum use of material, easy assemblage and quicker construction. The connectors are important components of the space frame system. The overall behavior and safety of the systems are mainly dependent on the connectors. For design of members and connectors, hollow tubular sections and hollow spherical joints have been considered respectively. Different parameters considered are outer and inner diameters of members as well as connectors for design of multilayered grid. Based on forces developed in the members, various groups for the members have been classified and design for each group has been presented. In the same line, for the design of connectors, critical locations of joints of the multilayered grid have been identified. Hollow spherical connectors at these critical locations have been modeled in ANSYS software and analysis has been carried out for the forces acting through the connected members. Design of hollow spherical connectors based on the stresses developed has been presented.

***Keywords**: Finite element analysis, Multilayer grid structures, Hollow spherical connectors, Hollow tubular sections, ANSYS.*

I. INTRODUCTION

As the grid depth is increased, either the angle of the diagonal bracing becomes more vertical and/or the grid spacing of the two horizontal layers must also be increased. Eventually the depth and grid spacing may be enlarged to such an extent that the compression members become excessively long. Thus they become heavy and un economical. In such situations it is possible to introduce an intermediate horizontal grid between the normal upper and lower chord layers. This additional layer allows the grid spacing of both outer layers to be reduced. Consequently, the length of the top compression chord members and the unrestrained length of the web compression members are reduced and an appropriate reduction in member cross-section. The intermediate layer carries very small load, but it provides lateral restrained against movement, stabilizing the whole structures and reduce the deflection considerably.

II. GEOMETRY OF MULTILAYER GRID STRUCTURE

A 60 m x 60 m Triple layer Space grid has been considered for the analysis. Structure is hinged supported on two opposite side every 10 m of span The length of the member is 2.5 m. Total height of top most layer of the grid is above ground level is 20 m assumed. The total depth of grid is 3.536 m from top most layered to bottom most layered. The Bottom layer’s length and width is 60 x 60 m, Centre layer length and width is 62.5 x 62.5 and top most layer’s length and width is 65 x 65 m. The structure is located at Ahmedabad, Gujarat, India. The geometry of the multilayer grid structure is shown in figure 1.

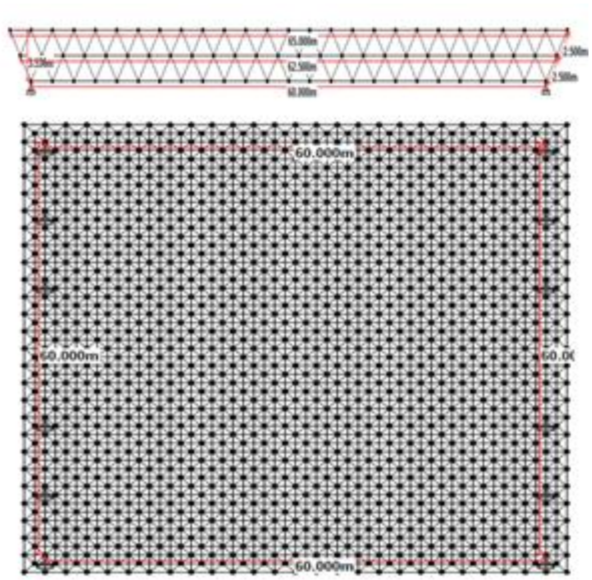


Figure1 Plan and elevation of the Multi layergrid

III. ANALYSIS OF MULTILAYER GRID STRUCTURE

Structure is analyzed under gravity load and wind load in STADD Pro software and models of connectors made in ANSYS 18.1 software. The sections used in space grid for the members are tubular.Preliminary property of the members has been provided as 165 mm outside diameter with 10 mm thickness for the analysis. For connector preliminary properties provided as 200 mm outer diameter and 140 mm inner diameter and 30 mm bolt diameter Calculation of different layers of the grid as shown in table 1.

Table1 Calculation of area of the grid

Roofing area (1.25m from edge of top layer in both direction)	67.5 m x 67.5 m		45556.25 m^2
Total Top layer Node	27x27=729 No.	65 m x 65 m	4225 m^2
Total Middle layer Node	26x26=676 No.	62.5 m x 62.5 m	3906.25 m^2
Total Bottom layer Node	25x25=625 No.	60 m x 60 m	3600 m^2

In the calculation of dead load of the structure, self-weight of the members and connectors, dead load of roofing material has been taken into account. Calculation of dead load and live load of the structure per node calculated and as shown in table 2.

Table2 Calculation of dead load and live load

Loading Condition	Per Node Forces

Dead Load of Roof	0.81875 kN
Dead Load of Connector	0.2115 kN
Live load	4.6875 kN

After dead load and live load calculation, wind load is governing force for the structure due height of 20m. Wind load is applied on the as per IS code 875 part III (2015).As shown in table fist to calculate force coefficient per node as per given procedure in IS 875 part III (2015).Wind Calculation as per IS 875 (2015) of the grid as shown in table 3.

Table3 Calculation of Wind load as per IS 875 (2015)

Terminology	**Symbol**	**Value**
Location	Ahmedabad, Gujarat.	
Structure Height	h	20 m
Roof Angle	φ	0 °
h/w	(20/65)	0.307
Basic Wind Speed	V_b	39 m/s
Risk Co-Efficient	k_1	1.06
Terrain and Height Multiplier	k_2	1.07
Topography Factor	k_3	1.0
Cyclonic Factor	k_4	1.0
Wind Directionality Factor	k_d	0.9
Area Averaging Factor	k_a	0.8
Combination Factor	k_c	0.9
Design Wind Velocity	$V_z = V_b \times k_1 \times k_2 \times k_3 \times k_4$	44.2338 m/s
Wind Pressure	$P_z = 0.6(V_z)^2$	1.174 kN/m^2
The Design Wind Pressure	$P_d = k_d \times k_a \times k_c \times P_z$	0.813 kN/m^2
Internal Pressure Coefficient	C_{pi}	± 0.7
Surface Area of Structural Element	A= 2.5 m x 2.5 m	6.25 m^2
Force Per Node	$F = (C_{pe} - C_{pi}) \times A \times P_d$	

Applied load on the structure as shown in figure 2.

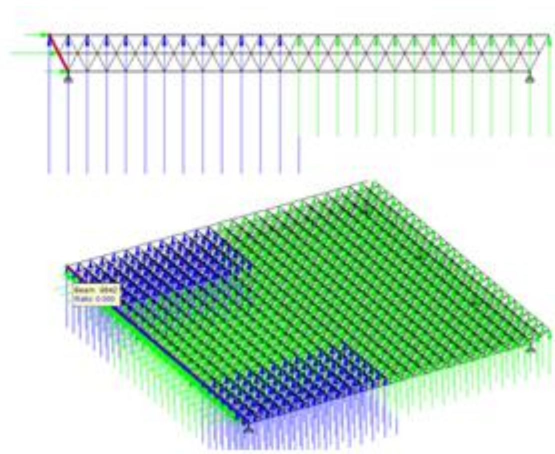


Figure 2 Elevation and 3D View of Wind load application on the Multi layer grid Structure.

Load combination applied on the structure as per IS 800:2007 and the load combinations are as following:

- 1.5 (DL + LL)
- 1.5 (DL ± WL)
- 1.2 (DL + LL ± WL)

IV. DESIGN OF MEMBERS AND CONNECTORS

Entire multilayered grid structure is divided into various groups based on forces generated in the members. Five groups have been considered for the design of the members and connectors.

- Group no.1 consists of 8674 members having range of forces 0 to 900 kN.
- Group no.2 consists of 252 members having range of forces 901 to 1200 kN.
- Group no.3 consists of 148 members having range of forces 1201 to 1500 kN.
- Group no.4 consists of 20 members having range of forces 1501 to 1800 kN.
- Group no.5 consists of 14 members having forces greater than 1800 kN.

Design of members for group 1

In the first group maximum Compressive forces developed in beamno. 10695.Connected Node of this beam are 1357 & 1357. Therefore, design of beam no. 10695 and connector at nodes 1357 & 1358 has been carried out.

Length of the member (L) = 2.5 m

Max compression force (C) = 900 kN

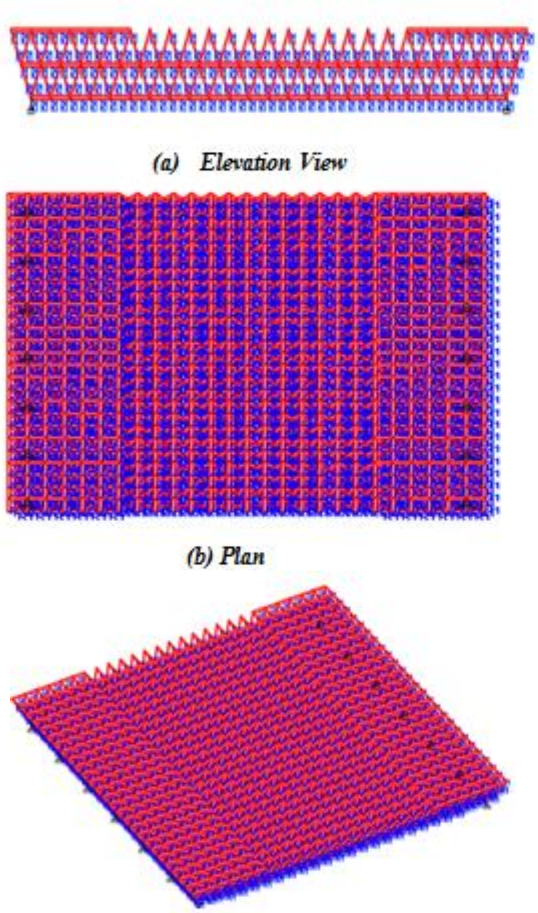
Max tension force (T) = 861 kN

Outside diameter = 155 mm

Inner diameter = 139 mm

Thickness of the member = 8 mm

Cross section area of the member (A) = 3692.6 mm^2



(a) Elevation View

(b) Plan

(c) 3D View

Figure 3 Members of Group 1

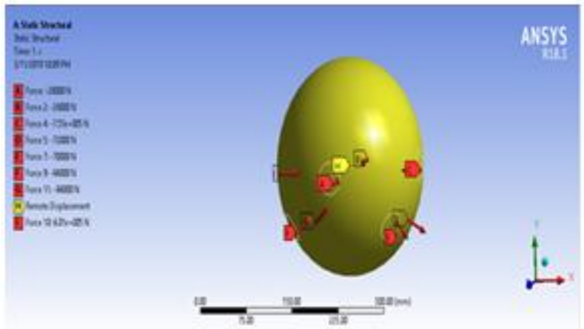
Radius of gyration = 52.048 mm
Yield stress (f_y) = 577 MPa,
Modulus of elasticity (E) = 200000 N/mm^2.
Slenderness ratio (λ) = L/R = 48.031
Euler buckling stress (f_{cc}) = (π^2 x E) / λ^2 = 854.748 N/mm^2
Effective slenderness ratio (λ_e) = $\sqrt{}$ (f_y/f_{cc}) = 0.822

Design compressive stress,
$f_{cd} = (f_y / \Upsilon_{mo}) / [\Phi + \sqrt{(\Phi^2 - \lambda e^2)}]$ = 372.964 N/mm^2………………….. (IS800:2007, 7.1.2.1)
Where, $\Phi = 0.5 \times [1 + \alpha (\lambda_e - 0.2) + \lambda_e^2]$ = 0.943.Whereα is Imperfection factor given in table 7 IS: 800-2007.
Design compressive strength (f_{cd}) = A_g x f_{cd} =1377.22 kN> 900 kN……………. (IS800:2007, 7.1.2)
Hence, Section is safe in compression.
Check for tension,
Design strength of yielding (T_{dg}) = ($A_g \times f_y$) / Υ_{mo}= 1936.96 kN > 861 kN. ………… (IS800:2007, 6.2)
Where, γ_{mo} is partial safety factor for failure in tension by yielding. (Υ_{mo} = 1.1).

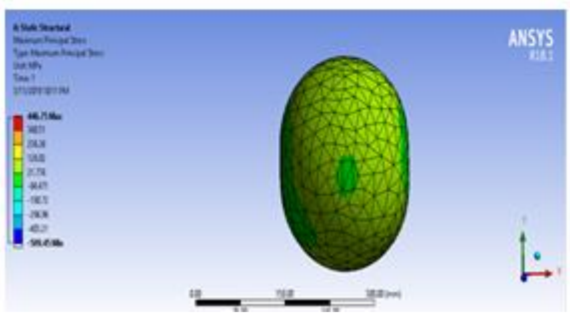
Design of connectors for group 1

Beam No. 10695 connects to node no. 1357 & 1358. So, these both nodes modeled analyzed in ANSYS software, to get maximum principal stress. For Node No: 1357, it is top layered node. Maximum compression force and maximum tension forces acted on the nodes are 755 kN and 72 kN respectively. ANSYS model of the connector at node no. 1357 as shown in figure 4.

(a) Rendered View



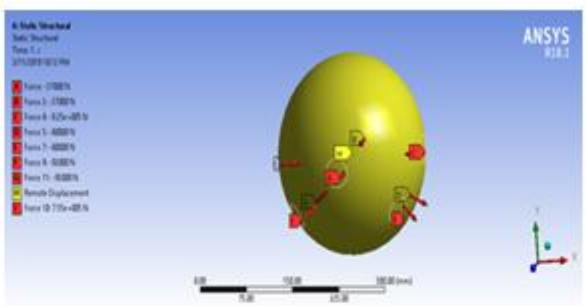
(b) Forces Applied on the connector



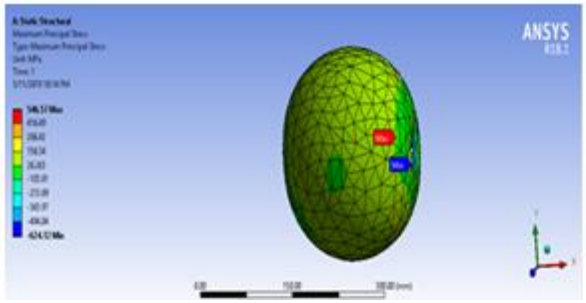
(c) Maximum Principal Stress

Figure 4Applied forces and Maximum principal stress in the connector for Node No: 1357

For Node No: 1358, it is top layered node. Maximum compression force and maximum tension forces acted on the nodes are 925 kN and 80 kN respectively. ANSYS model of the connector at node no. 1358 as shown in figure 5.



(a) Forces Applied on the connector

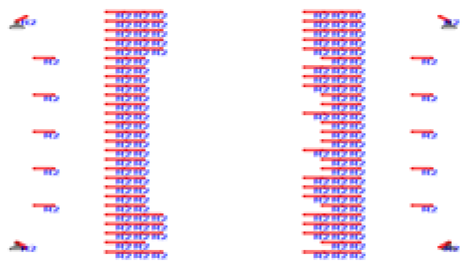


(b) Maximum Principal Stress

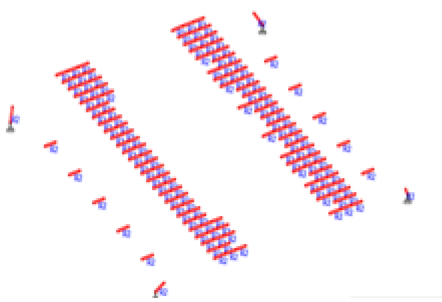
Figure 5 Applied forces and Maximum principal stress in the connector for Node No: 1358

Same procedure for group 2, 3, 4 and 5 has been done as shown in figure 6, 7, 8, 9, 10 and 11

(a) Elevation View

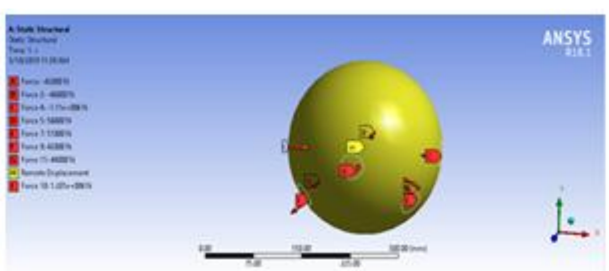


(b) Plan

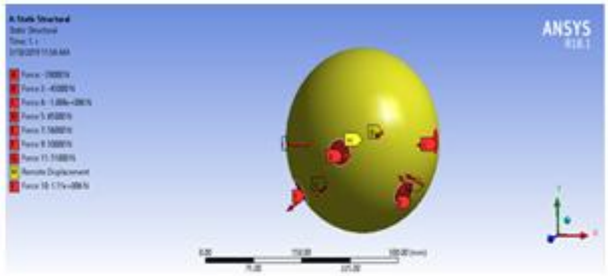


(c) 3D View

Figure 6 Members of Group 2



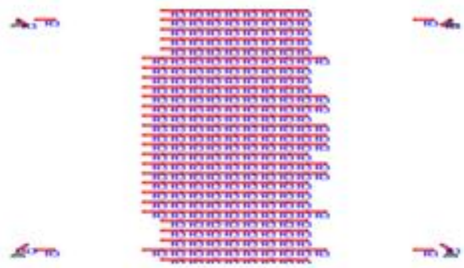
(a) Forces Applied on Node No. 1504



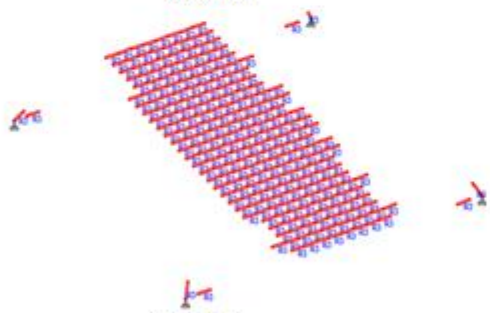
(b) Forces Applied on Node No. 1505

Figure 7 connectors of Group 2

(a) Elevation View

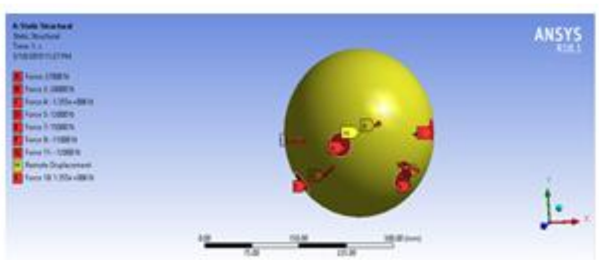


(b) Plan

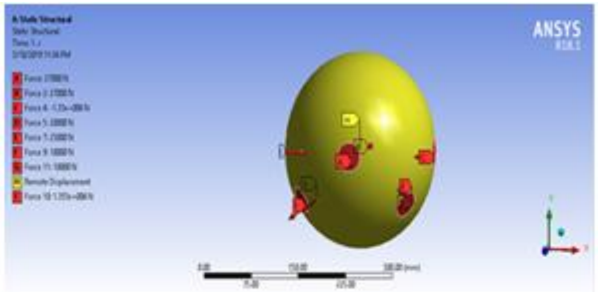


(c) 3D View

Figure 8 Members of Group 3



(a) Forces Applied on Node No. 1608



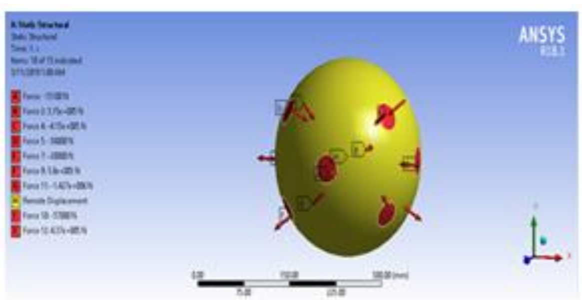
(b) Forces Applied on Node No. 1609

Figure 9 connectors of Group 3

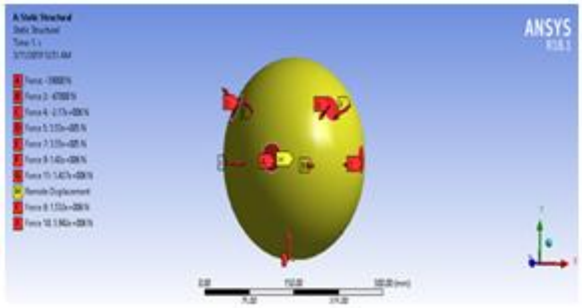
(a) Elevation View

(b) Plan

Figure 6 Members of Group 4



(a) Forces Applied on Node No. 2444



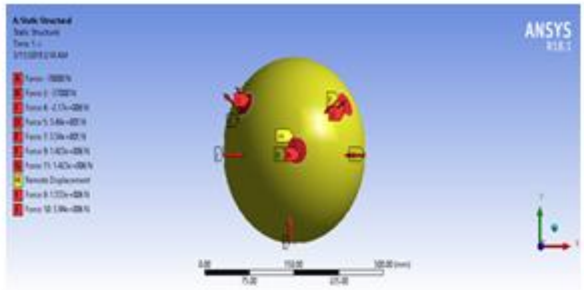
(b) Forces Applied on Node No. 3401

Figure 10 connectors of Group 4

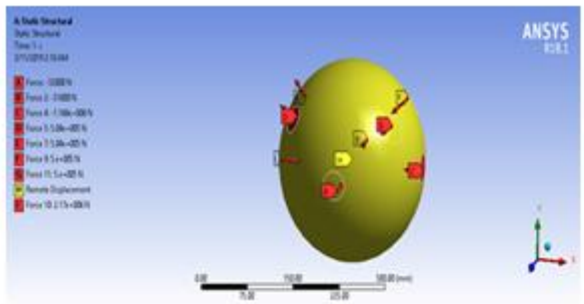
(a) Elevation View

(b) Plan

Figure 7 Members of Group 5



(a) Forces Applied on Node No. 3301



(b) Forces Applied on Node No. 3302

Figure 11 connectors of Group 5

V. RESULTS & DISCUSSION

Entire multilayered grid structure classified into various groups based on forced developed in the members and properties given to these groups accordingly. The size of members shows in the table 4. Outer diameter of each group remains the same, but thickness increases as forces increases.

Table 4 Summary of Design of Members

Group No.	Force Range	Outer Dia.	Thickness	No. of Beams
	(kN)	(mm)	(mm)	
1	≤ 900	**155**	**8**	8674
2	901-1200	**155**	**12**	148
3	1201-1500	**155**	**12.5**	252
4	1501-1800	**155**	**16**	20
5	≥1801	**155**	**16**	14

After applying design property deflection of the structure should be less than allowable deflection limits. Allowable vertical deflection = Span/300 = 200 mm and Allowable lateral deflection = Height/300 = 66.66 mm. In the present illustrative

Multilayered grid structure deflection after applying Design property, maximum vertical deflection is193.82 mm < 200 mmand maximum lateralDeflection is 54.22 mm < 66.66 mm. (o.k.) Based on classification of groups, sizes of the Connectors demonstrated in the following table. Outer diameter and bolt diameter of all group connector remains the same, but thickness increases accordingly as shown in table 5. Maximum principal stress in the connectors should be less than 577 MPa.

Table 5 Summary of Design of Connectors

Group No.	**Beam No.**	**Node No.**		**Outer Dia.**	**Inner Dia.**	**Bolt Dia.**	**Thickness**	**Weight**	**Max. Principal Stress**
				(mm)	(mm)	(mm)	(mm)	kg	(N/mm^2)
1	10695	1357	1358	**240**	190	35	**25**	28.613	**546.57**
2	10972	1504	1505	**240**	180	35	**30**	32.832	**512.65**
3	11180	1608	1609	**240**	150	35	**45**	42.926	**323.49**
4	26652	3401	2444	**240**	120	35	**60**	49.692	**558.65**
5	30589	3301	3302	**240**	120	35	**60**	49.692	**558.55**

VI. CONCLUSION

- In large multilayer grid structures, maximum deflection occurs at Centre of two opposite exterior edges along span of top layer of the grid due to the load combination of 1.2(D.L. + L.L. – W.L. Z Suction).
- In large multilayer grid structures, maximum axial forces develop in the bottom layer members, which are connected directly to the supports due to the load combination of 1.5(D.L. – W.L. Z Suction).
- After analysis of multilayer grid structure, it has been investigated that forces developed in top layer member's increase from supports to central region. Therefore, size of members increases accordingly.
- Considering allowable maximum principal stresses the design weight of connectors for group no. 1, 2, 3, 4 & 5 are evaluated 28.61 kg, 32.83 kg, 42.92 kg, 49.69 kg &49.69 kg respectively

REFERENCES

1. *"An Explanatory Handbook on Proposed IS 875 Part 3 (1987) Wind Loads on Building and Structures," IIT Roorkee.*
2. *A.L. Koushky, G. Dehdashti and A. Fiouz,"Nonlinear Analysis of Double-layer Grids with Compositive Nodes under Symmetric and Unsymmetrical Gravity Loads," International Journal of Space Structures (2007), Vol.22, No.2*
3. *Dr. Bayar JafarAlsulayfani, TarekEdreesSaaed,"Optimization of Space Frame Design," International Conference on Innovative and Smart Structural Systems for Sustainable Habitat (INSHAB-2008), Coimbatore.*
4. *Henning, "Optimum Geometry Design of Double Layer Space Trusses," Journal of Structural Engineering(1986), Vol. 112.*
5. *IS 875 Part 3 (2015), "Indian Standard Code of Practice for Design Load (Other Than Earthquake) for Buildings & Structures (Third Revision)," Bureau of Indian Standard, New Delhi.*
6. *IS 875 (1987), Indian Standard Code of Practice for Design Load (Other Than Earthquake) For Buildings & Structures. (Second Revision)," Bureau of Indian Standard, New Delhi.*
7. *IS 800 (2007), Indian Standard Code of Practice for General Construction in Steel (Third Revision)," Bureau of Indian standards, New Delhi.*

8. *IS 806 (1986), Code of Practice for use of Steel Tubes in General Building Construction (Fifth Revision)," Bureau of Indian Standards, New Delhi.*
9. *IS 1161 (2014), Steel Tubes for Structural Purposes-Specification (Fifth Revision)," Bureau of Indian Standards, New Delhi*
10. *Mehdi Ebadi, Dr. MohammadrezaDavoodi. "Evaluate Axial Stiffness of the Mero Connection, under the Effect of Hardening the Screw," International Journal of Science &Emerging Technologies (IJCSET), (2012), Vol. 4.*
11. *Mohammad Reza Davoodi, JavadVaseghiAmiri, SirousGholampour, Seyed Amin Mostafavian. "Ball Joint Behavior in a Double Layer Grid by Dynamic model updating," (2012)*
12. *M. Dehghani, M. Mashayekhi and E. Salajegheh"Topology optimization of double-and triple-layer grids using a hybrid methodology,"(2015)*
13. *Nidhi A. Mehta, V. A. Arekar &Atul N. Desai. "Analytical Study on Hollow Space Grid Connector," International Journal of Science Technology & Engineering (IJSTE), (2016), Vol. 2, Issue 9.*
14. *N. Subramanian. Principles of Space Structur.by Wheeler Publishing, Berlin, 1981.*
15. *O. Caglayan, E. Yuksel "Experimental and finite element investigations on the collapse of a Mero space truss roof structure – A case study,"(2007), Engineering Failure Analysis.*
16. *V. A. Arekar & B. B. Bhavsar, " Analytical Study of Mero Connector in Double Layer Grid Structure," International Journal of Latest Trends in Engineering and Technology (IJLTET),(2013) Vol. 2, Issue 2.*
17. *V. A. Arekar & Neil D. Sheth, "Comparison of Principal Stresses in Space Structure Connectors," International Journal of Latest Technology in Engineering Management & Applied Science (IJLTEMAS),(2014), Vol. 3, Issue 5.*