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Optimization of Space Frame Structures

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Abstract Space **trusses/frames are 3-D structures assembled of linear elements. These elements are arranged in a way to ensure 3-D force transfer from load application point to supports. A Space frame or space structure is truss like light weight rigid structure constructed from interlocking struts in geometric pattern. In past years, there is rapid increase in number of steel structure because of its structural potential and visual beauty. These have factors such as large indoor space, sports tournament, cultural program held under one roof. From the study, we noticed that the steel space frames are optimized, analyzed in different ways such as practical experiments were performed or using software as a tool for optimization via different codes such as Euro-code3, BS code 5950 (Part 1): 1989 etc. These codes give the design procedure of space frame and the property of material to be used. As the Indian codes can also be used in the design of steel space frame. Therefore, using IS codes for calculating loads, assigning properties, and designing the space frame. Also analyzing frame with the help of software STAAD Pro. This fully supports the Indian Codes.**

Keywords —Double layer grid, Geometry optimization, Member Design, Steel space frame, Strut design, Utilization Ratios.

I. INTRODUCTION

The steel structures are usually constructed to the building type such as assembly halls, auditoriums, exhibition pavilions, warehouses, workshops etc. They are not only used over large span roofs, but also mid span, short span encloses as roofs, floors, canopies etc. The material used for the space frame is timber and steel. Timber therefore used in 19th century, causes high maintenance cost therefore uneconomical. Steel now-a-days most commonly used material in spaced frame sustains more load and can carry tones of weight also providing proper maintenance and economical to use over large span.

The members are the axial elements with circular or rectangular sections. All members can only resist tension and compression. A space grid is built of relatively long tension members and short compression members.

These structures are statically indeterminate and their structural manual calculation is very tedious. Thus, using computer program as tool to analyze the complex space structure with great accuracy and less time. There are three types of space frames, as follows *1* - Skeleton Framed Work *:-* These Skeleton framed work is also known as braced framed work, usually consists of double or multiple grids, braced plates, domes etc. these are most used system as the variations in geometric forms are possible.*2* - Stressed Skin Structures *:-* These are type of rigid construction, the frame with non loaded coverings, such as stressed skin folded plates, barrel vaults, stressed skin domes etc. *3* - Suspended Structures *:-* The structures in which floors are supported by cables, tendons etc. such as cable roof. Hence we are optimizing the space frame structure, over an area of 60m x 60m with existing model to new optimized model with all the loading conditions and design procedure as per Indian Standards; the model which was redesigned is of Abhay Prashal Sports Club, Table Tennis Roof of Space Frame at Race Course Road in Indore, India.

Some special features of space frame are discussed as follows -

- They are light, structurally efficient and use materials optimally.
- They are an elegant and economical means of covering large column-free spaces for a variety of applications such as sports structures, auditorium, aircraft hangars and assembly halls.
- Because space frames are put together by using precise factory made components, skilled labour employed on site for assembly and erection is minimal.
- Services such as lighting and air conditioning can be integrated with space frames.
- Space frames save construction time, because they use factory produced components that can be manufactured by fast production techniques, transported to the site and erected easily.

Advantages of using Hollow Sections or Steel Pipes are -

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- As moment of inertia increases load carrying capacity also increases as compared to other steel members.
- Circular or tubular sections give the maximum resistance towards torsional effect, or it can be said as they give best torsional resistance.
- These are area of interest for architects for providing these sections in aesthetic view.
- The circular surface of the section reduces the possibility of corrosion, as it does not collect dust and moisture.

II. METHODOLOGY (PART – 1)

PART 1: APSC Existing Space Frame Structure

GEOMETRY

The steel space frame of Abhay Prashal was designed in 19's, which consist of two layered grid system with squares and rectangular based pyramids. The plan area on which the space frame rests is of 60m x 60m at height of 12.8m from ground level.

The existing space frame forms the model of square and rectangular based pyramids of two layered grid system. The bottom grid lies in a single plane whereas the top grid forms some slope with respect to bottom grid. The distance of top and bottom grid at the central part of frame is 2.5m ending the slope to end with the distance of 1.8m in height. Therefore, confirming proper drainage of rain water from roof.

ASSEMBLAGE OF STRUCTURE

The APSC space frame consists of members and connections arranged in a way to ensure 3-D force transfer from load application point to support. Top grid members are inclined to drain off the rain water etc., whereas bottom chord members are straight in a plane at height of 9.44 meters from plinth level 0.83m filling from ground level till plinth level. The distance between top grid and bottom grid at center is 2.5m and at end it tends to 1.8m at columns.

The members in space frame are from IS-codes with commercial grade of steel (250MPa). Top and bottom chord members with circular cross-section of 300mm outer diameter with thickness of 5.4mm, whereas inclined members connecting both top and bottom chord members having outer diameter 150 mm with 5.4mm thickness. These steel members or pipes are Cold Rolling Manufactured to reduce stresses, and seamless to reduce the effect of change in temperature which can cause some failure such as leakage etc.

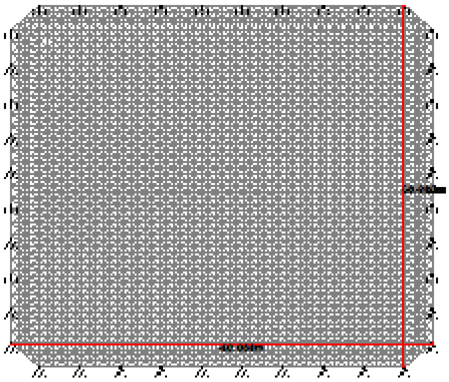

Fig 1 - Plan View of Existing Space Frame; Line Model of APSC over an Area of 60m x 60m.

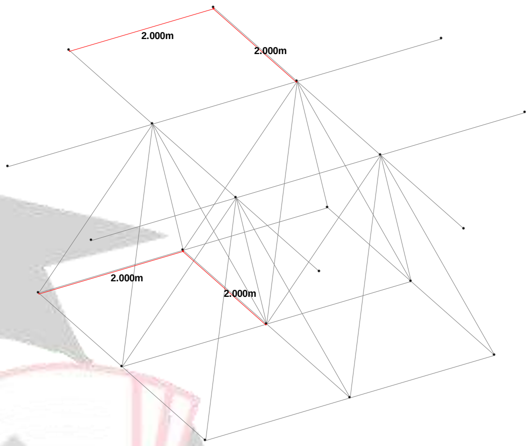

Fig 2 - A Part View of Space Frame Joining Top and Bottom Grid Members.

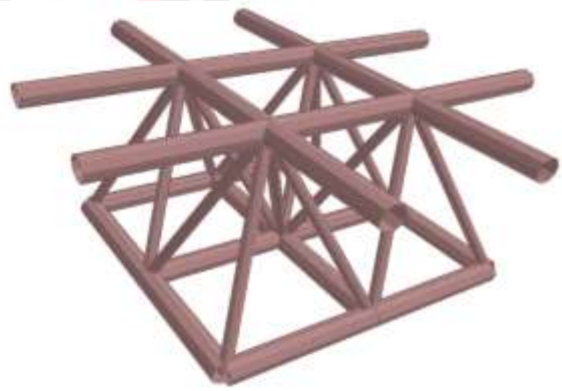

Fig 3 - Rendered View of Space Frame.

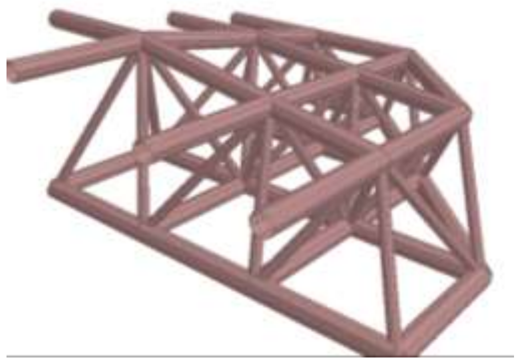

Fig 4 - Rendered View of Space Frame Showing the Slope in Top Grid.

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SUPPORT CONDITION

The whole steel space frame rests on RCC columns at its periphery, resulting in column free area. Therefore, the columns are placed at 6.5 to 7 meters centre to centre at the periphery of space frame. All the RCC columns are connected to beams or further it can be said as beam blocks. These beam blocks consist of foundation bolts. Arrangement of 12mm thick MS plate on foundation bolts, about 50mm thick neoprene thick polymer (high density rubber material), on polymer again there is 12 mm thick MS plate. Therefore, Steel pipes are welded to all the plates forming the periphery of the structure and then the whole space frame rests on the plates and connected to column with joints.

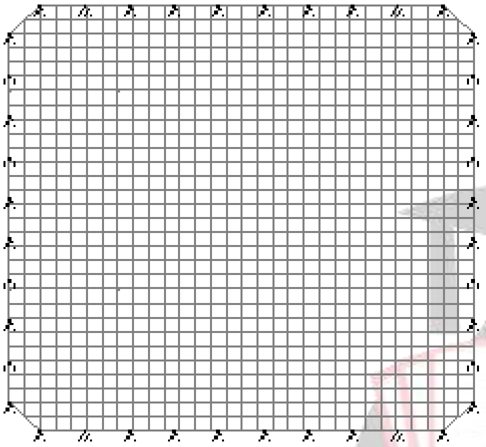

Fig 5 - Bottom Grid Plan with Mesh Size 2m x 2m, with Column Placement.

LOADINGS

The space frame was designed in 19's on the area 60m X 60m, at the time of erection there were no nearby buildings or high-rise near to several meters, therefore considering wind loads with factor taking no obstruction near to site lies in category a and the height of space frame is 12.8m from ground level.

APSC space frame was so designed for the dead load of cement roofing on space frame, of 70 tones load, or considering an area load of AC sheet as 171 N/mm^2.

Purlin are placed at the distance of 1.25m centre to centre on the space frame, so the purlin loads are taken in form of uniform distributed load in one direction in KN/m.

Also, the frame was designed for fall ceiling and cat-walk on the space frame, but this live load is considered at the bottom grid of space frame, of 650N/mm^2. And live load on sheet as per IS 875 part 2 is 750N/mm^2 for slopes less than or equal to 10 degrees.

ANALYSIS

The whole structure is analyzed in STAADPro.v8i software, with the geometry, properties and loadings discussed above.

The load combination was taken from IS800:1984 are as follows:

1. DL + LL
2. DL + WL ± X
3. DL + LL + WL ± X
4. DL + WL ± Z
5. DL + LL + WL ± Z

DISCUSSIONS

The above results clearly shows the utilization ratio of the space frame, as the periphery members are less utilized shown in orange color showing utilization ratio up to 0.5 that means the members are 50% utilized but as we go closer towards the centre the members are more utilized showing in green color with utilization ratio up to 0.87 that means the members at the centre are more stressed and utilizes member up to 87%. Therefore, it also clears the concept of stress distribution in the space frame.

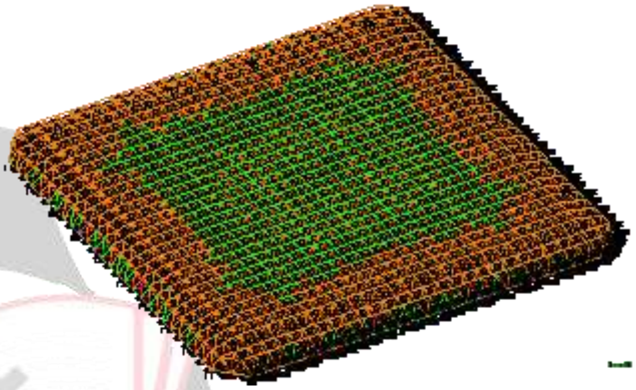

Fig 6 - Utilization Ratios of the Existing Space Frame, After Analysis.

III. METHODOLOGY (PART – 2)

PART 2: Optimized Space Frame Structure of APSC

GEOMETRY

As we studied from the existing structure of APSC, we analyzed that the stress distribution is more towards centre and continuous to decreasing towards end condition of space frame.

The same length of members used in space frame gives less utilization ratio at the periphery but the same members at the centre gives more utilization ratio.

The conceptual diagram further describes that the top and bottom grid members have maximum depth at centre and reducing the same depth till end condition, which forms the shape of dome at top grid and bottom grid members are lying in same plane.

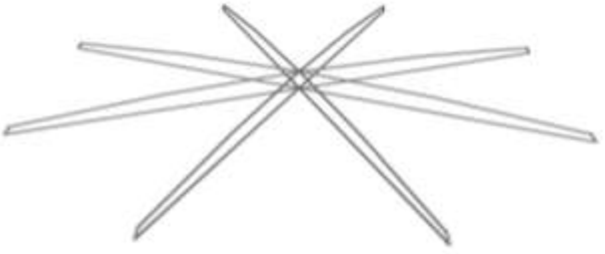

Fig 7 - Conceptual Image of Geometry of Optimized Space Frame.

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ASSAMBLAGE OF STRUCTURE

The above concept is made to give a proper flow to rain water for drainage, and also from aesthetic point of view, the shape given is related to dome in space frame.

The top grid forms the dome shape as giving maximum distance to bottom grid at centre and minimum distance at the end of space frame.

The top and bottom grids consists the mesh of 2.5m x 2.5m, these meshes forms the square bases to the pyramids form between top and bottom grid. The pyramids forms are the inclined members connecting both the grids node to node and help in 3-D transfer of stresses to the support point.

Table 1 - Geometry of Optimized Space Frame

S.No.	Grid With Mesh	Mesh Size
1	Top Grid	2.5m x 2.5m
2	Bottom Grid	2.5m X 2.5m

Table 2 - Geometry of Optimized Space Frame

S.No	Members	Property	OD	Thickness	YST (MPa)	UST (MPa)
1	TOP GRID	CHS	90 mm	4.8 mm	310	450
2	BOTTOM GRID	CHS	90 mm	4.8 mm	310	450
3	INCLINED	CHS	80 mm	4.5 mm	310	450

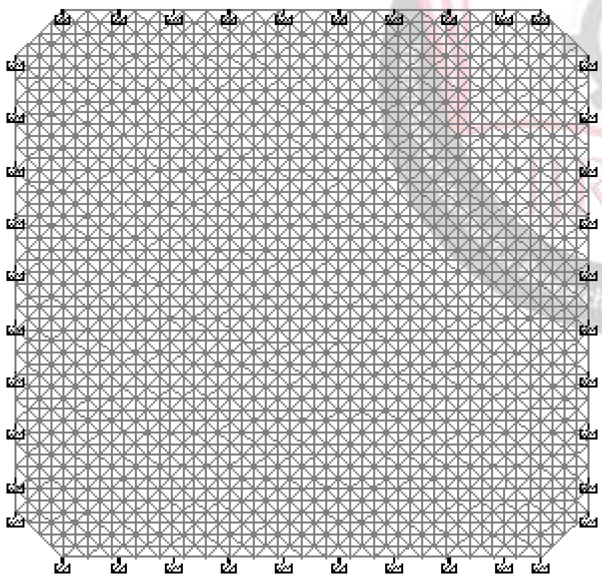

Fig 8 - Optimized Space Frame Model of APSC

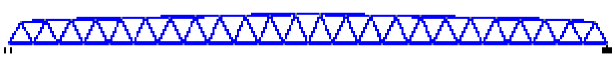

Fig 9 - Sectional Elevation of Optimized Space Frame

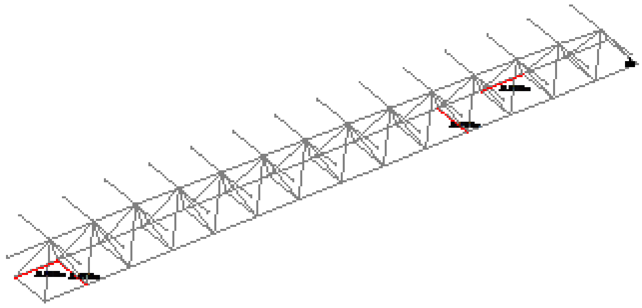

Fig 10 - Elevation View of Optimized Space Frame Showing Slope

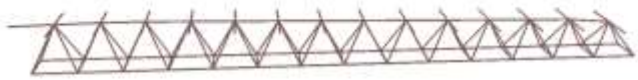

Fig 11 - Rendered Elevation View of Optimized Space Frame with Top Grid Slope

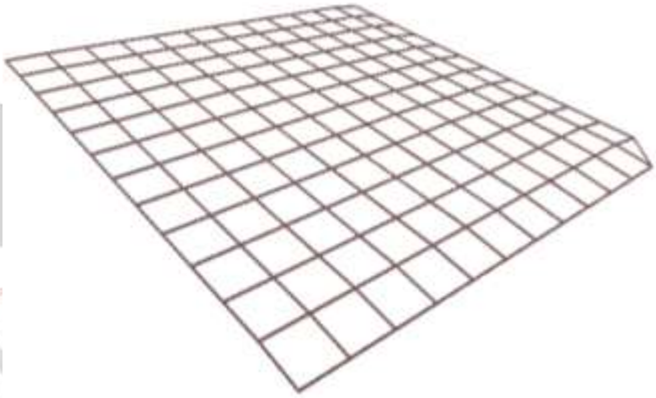

Fig 12 - Rendered Elevation View of Optimized Space Frame of One-Fourth Top Grid Slope.

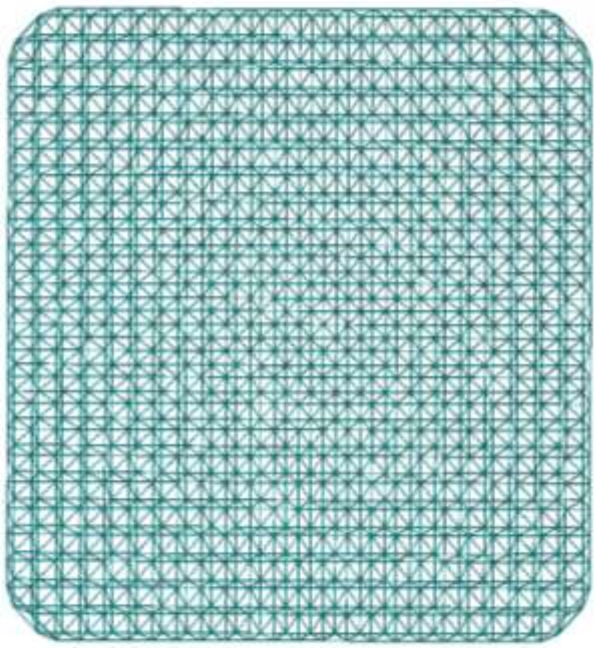

Fig 13 - Rendered View of Optimized Space Frame of APSC

SUPPORT CONDITION

The support condition of the optimized space frame is same as previous model.

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DESIGN SPECIFICATION (as per IS 800:2007)

MATERIAL

All the structural steel used in the construction of space frame are falling under the preview before fabrication are confirming to code IS2062.

These are also specified in IS800:2007, Table-1, Pg.no.-14, as yield strength 310MPa and ultimate strength as 450MPa.

OBJECTIVE

The objective of designing is to achieve acceptable probability that structure will be serviceable and safe during the design life of it. With proper factor of safety it should restrain all the deformations and loads, during and after construction, also resistance to accidental loads and should not collapse before giving warnings in any situation.

METHOD OF DESIGN

The structure is designed by Limit State Method, from IS 800:2007, which takes into account of theories, experiments and experience.

LOADS AND FORCES

- Dead Loads
- Imposed / Live Loads (as per IS 875 Part-2 -1987, Reaffirmed 2003)
- Wind Loads (as per IS 875 Part-3 – 2015)

SECTIONAL PROPERTIES

- Area of Cross-Section (a) = $A = \frac{\pi}{4}OD^2 - \frac{\pi}{4}d^2$ (mm^2)
- Moment of Inertia about both the axis will be same, $I_{xx}, I_{yy} = \frac{\pi}{16}(OD^4 - d^4)$ (mm^4)
- Elastic Section Modulus, **Ze** = $\frac{\pi(OD^4-d^4)}{32\times OD}$ (mm^3)
- Plastic Section Modulus, **Zp** = $\frac{(OD^3-d^3)}{6}$ (mm^3)
- Radius of Gyration, $r_{xx}, r_{yy} = \sqrt{\frac{I}{A}}$ (mm)

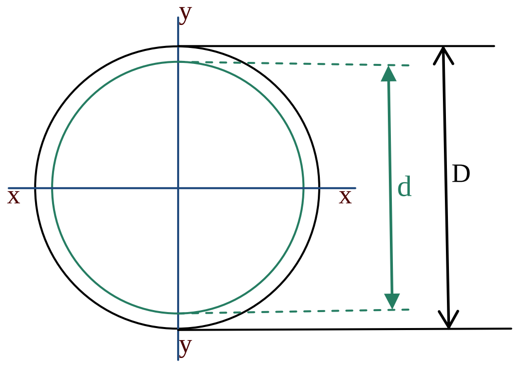

Fig 14 - Cross Section of Hollow Circular Section

CLASSIFICATION OF CROSS – SECTION

As per IS 800 : 2007; Clause 3.7; In steel the cross sections are classified as per the local buckling under compressive stresses are as follows :

A. **Plastic Sections / Class 1:** these sections forms plastic hinge at ultimate tensile stress, therefore have capability against rotation.

B. **Compact Sections / Class 2:** these sections can form resistance to plastic moment but cannot develop plastic hinge, they doesn't have rotational resistance.

C. **Semi-Compact Sections / Class 3:** in these sections extreme fiber can reach yield stress, but fails to develop resistance against plastic moment.

D. **Slender Sections / Class 4:** these are the sections in which elements buckle locally before extreme fiber reaches yield stresses. These sections are than designed using IS 801:1975(R2001).

Therefore, Table -2 from IS800:2007, gives the limiting width to thickness ratios for the section classification.

CALCULATION OF LOADS

Load Calculations (As per IS 800:2007)

1) Dead Load (DL)

i) Self weight of structure

ii) GI / Metal Sheet = 85 N/m^2 = 0.085 KN/m^2

iii) Purlin Load Calculation:

Area = 3m x 1.5m = 4.5m^2

Load of 1 Purlin = 6Kg/m = 0.058 KN/m x 3m = 0.174KN

Area Load = 0.174 KN/4.5m^2 = 0.0386KN/m + 1.5% of 0.116 KN/m = 0.00174 KN/m

Total Load by Purlin = 0.1177 KN/m

2) Live Load (IS 875 – P (2) – 1987 Reaffirmed 2003)

i) Catwalk (on bottom grid) = 0.65 KN/m^2

ii) Live Load on top grid; Roof Angle up to 10° = 750 N/m^2

3) Wind Load (As per IS 875(Part 3): 2015)

V_z = Design wind speed (m/sec) (clause 6.3)

$V_z = V_b \times K1 \times K2 \times K3 \times K4$

V_b = Basic wind speed = 39 m/sec

k_1 = Risk Coefficient for different Structures from Table – 1 ; k_1 = 1.0 (clause 6.3.1)

k_2 = Category 3 – terrain roughness and height factor (ht = 12.8m) k_2 = 0.944 (clause 6.3.2)

k_3 = topography factor ; k_3 = 1.0 (clause 6.3.3)

k_4 = cyclonic region importance factor; k_4 = 1.0 (clause 6.3.4)

$P_z = 0.6\ V_z^2$; Wind Pressure (clause 7.2)

$P_z = 0.6\ (36.81)^2$

P_z = 813.25 N/m^2

Area averaging factor, k_a = 0.8, (clause 7.2.2, Table -4)

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Wind directionality factor, $k_d = 1.0$, (clause 7.2.1)
Combination factor, $k_c = 0.9$, (clause 7.3.3.13)
$P_d = P_z \times k_a \times k_d \times k_c$
Where, $k_a \times k_d \times k_c \geq 0.70$
$0.8 \times 1 \times 0.9 = 0.72 > 0.7$ Hence OK
$P_d = 813.25 \times 0.72$ N/m^2
$P_d = 585.54$ N/m^2

$P_d = 0.586$ KN/m^2 (Wind Intensity)

Opening % = Open Area / Total Area = 0.025% / 2.5%
Permeability up to 5% to 20% = $cp_i = \pm 0.5$
External pressure coefficients for roof (cp_e) from IS 875 - P (3) – 1987, (Table – 5)
h = 12.84 m, w = 60 m
h/w = 12.84/60 = 0.215 < (0.5)
Roof angle = 0°

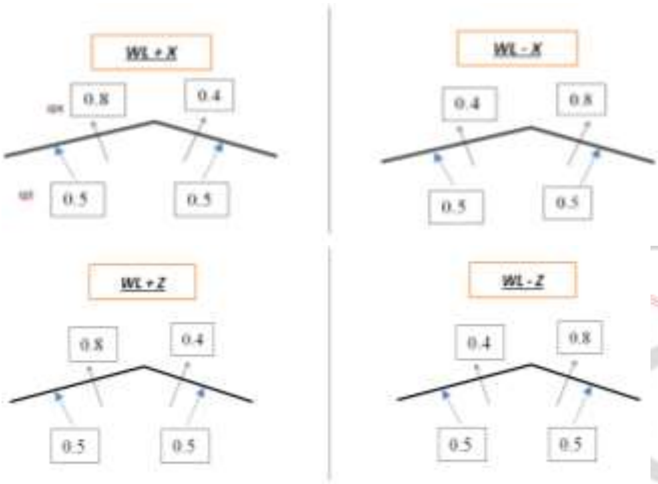

Fig 15 - Wind Internal and External Pressure Coefficient of Roof

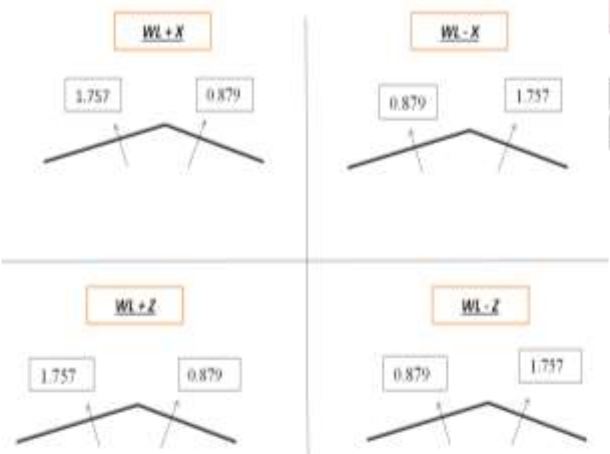

Fig 16 - Wind Intensity in all the Directions

These Wind Intensity are then converted to line loads and applied to model as line load on the top grid member of the space frame

DESIGN CRITERIA (as per IS 800:2007)

A. TENSION (Section 6)

Design of Tension in steel members is governed by minimum value from design strength from yielding, rupture or block shear.

B. COMPRESSION (Section 7)

Section 7 describes the compression member design which includes non dimensional effective slenderness ratio, imperfection factor, effective slenderness ratio etc.The hollow sections lies in the buckling **class-a** from table-10, which confirms that hollow sections have best or maximum resistance to buckling.

Computing them in the procedure described in IS800:2007, we get the compressive strength of the member.

C. BENDING AND SHEAR (Section 8)

As per Clause 8.2.2; the code says hollow sections are laterally supported members that further describes that hollow sections does not face any lateral torsional buckling failure. The process to check the bending strength of the member described in laterally supported members. (Claus 8.2.1.2)

Now the section is to be checked as per clause 8.4, for low and high shear in which area to be considered in shear in hollow sections is described as (2bt), that this much area will resist the shear in hollow section and further the shear capacity calculations are done.

D. COMBINED ACTIONS (Section 9)

There are two types of combined actions:-

1- Compression + Bending
2- Tension + Bending

Checking the member against combined actions confirms the sectional strength of the member as cross-section should not fail under local effects, and another is overall strength of the member that the member should not fail under external loading conditions, buckling etc.

Therefore, by the keeping above criteria in mind we generated an excel sheet which checks all the above designs explained as per IS 800:2007, and also cross checked with the STAAD model results and Manual results.

RESULTS

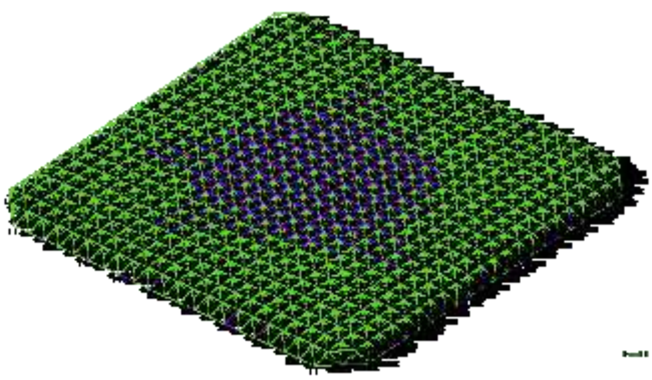

Fig 17 - Utilization Ratios of Optimized Space Frame Structure, After Analysis.

CONCLUSION AND DISCUSSION

The above figure clearly shows the utilization ratios of the structure the green colored part is now more utilized 0.86

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near to it, that means by reducing the size of member, the member gets more utilized and the increasing size of the mesh gives more utilization to inclined member and only top grid members at centre are more utilized purple in color as compared to periphery grid.

Therefore, we can easily conclude that members are fully optimized and used up to maximum extent.

It is also clear that by increasing the size of space frame we get less stresses at the centre, as the previous model have less member length and more stresses, by studying that we provided member with increased length.

The whole study and research work clearly shows that we optimized the members of steel space frame in such a way that the member length gets increased from 2 m to 2.5 m with some change in top grid forming slope, the member properties are of steel grade 310MPa, from TATA CHS of OD 90mm and 4.8mm thickness, gives the more utilized sections in the frame.

These sections are also checked manually against tension compression, bending, shear and combined actions, in which they all are again checked at member level strength and at section level strength.

CAPACITY CHECK FOR HOLLOW CIRCULAR SECTIONS

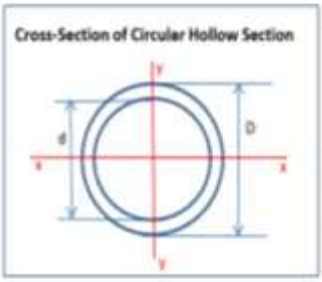
As per IS 800:2007

Property Name - circular hollow section 2919

** Sectional Properties of the Member **

Nominal Bore	d	=	67.1 mm
Outside Diameter	D	=	76.1 mm
thickness	t	=	4.5 mm
Area of cross section	A	=	1011.708 mm²
Moment of Inertia	I_{xx}, I_{yy}	=	650883.61 mm⁴
Section Modulus	Z_{xx}, Z_{yy}	=	17106.008 mm³
Radius of Gyration	r_{xx}, r_{yy}	=	25.36437 mm

Cross-Section of Circular Hollow Section



** Material Properties **

fy	=	310 N/mm²
fu	=	450 N/mm²
E	=	205000 N/mm²
ν	=	0.3
G	=	78846.154 N/mm²
r	=	0.8998265 N/mm²

** Partial Safety Factors **

γ_{m0}	=	1.5
γ_{ml}	=	1.1

** Analysis Results **

length of member	l	=	2.53 m
Effective length of member	l_{eff}	=	2.53 m
Bending Moment @ Major Axis		=	0.0016 KN-m
Bending Moment @ Minor Axis		=	0.0016 KN-m
Shear Force Major Axis		=	84.54 KN
Shear Force Minor Axis		=	84.54 KN
Axial Compression Force		=	53.6 KN

1 Section Classification

D/t = 16.911

PLASTIC - SECTION

2 Design for Compression

Buckling Class	=	a	Table - 10 , Pg.no.-44
Imperfection Factor (α)	=	0.21	Table - 07 , Pg.no.-35

Calculations

l_{eff}/r	=	99.7		
f_{cc}	=	203.2	N/mm²	
λ	=	1.2		
ø	=	1.4		
f_{cd}	=	105.0	N/mm²	Design Compressive Stress
Compressive Force	=	106244.58	N	

Compr. Capacity = 106.24 KN

3 Design for Shear

Shear Area	A_v	=	644.4	mm²
	V_p	=	115333.80	N

Shear Capacity = 115.33 KN

4 Design for Bending

d/t	=	14.91		LOW SHEAR CASE
V_d	=	115.33	KN	
0.6 V_d	=	69.20	KN	
V_u	=	84.54	KN	LOW SHEAR
Elastic Section Modulus (Ze)	=	17106.01	mm³	
Plastic Section Modulus (Zp)	=	23090.90	mm³	
Design Bending Strength (Md)	=	4773978.30	N-m	

Bending Strength = 4773.98 KN-m

5 Design for Tension

i)	Yielding	T_{dg}	=	285117.71	N
	Yielding tensile Strength		=	285.12	KN
ii)	Rupture	T_{dn}	=	372492.49	N
	Yielding Strength in Rupture		=	372.49	KN
iii)	Block Shear	T_{db}	=	493208.53	N
				493.21	KN
		T_{db}	=	445650.82	N
				445.65	KN

Tension Strength = 285.117709 KN

6 Combined Axial Force and Bending Moment CHECK @ Section Strength

Parameters :-

N	=	53.6	KN	
N_d	=	209.09	KN	
n	=	0.26		
M_d	=	4773.98	KN-m	
M_{nd}	=	4474.10	KN-m	
α	=	2		Table - 17, Pg.no.- 71

CHECK 1.279E-13 **HENCE SAFE**

7 Bending and Axial Tension CHECK @ Member Strength

Parameters :-

P	=	53.6	KN		
Pd	=	106.24	KN		
M	=	0.0016	KN-m		
Md	=	4773.98	KN-m		
λ	=	1.24			
n	=	0.50			
K	=	1.32		≤	1.40
K	=	1.40			
C_{my}, C_{mz}	=	0.9			
C_{mLT}	=	0.9			
λ_{LT}	=	1.22			
K_{LT}	=	0.90		≥	0.92
K_{LT}	=	0.92			

1st Interaction Equation: 0.50 ≤ 1 **OK**

2nd Interaction Equation: 0.50 ≤ 1 **OK**

Fig 18 – Manual Calculation excel Sheet Generated.

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