OPTIMIZATION OF SPACE FRAME STRUCTURES FOR ENHANCED STRUCTURAL EFFICIENCY

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Abstract : This study presents a comprehensive optimization approach for space frame structures, aiming to minimize structural failure while maintaining structural integrity. The design and optimization of space frames involve advanced mathematical techniques and software tool to analyse various design parameters, such as geometry, material properties, and load conditions. space frame in the form of double layer space grids formed by two meshes where the bottom of the structure is termed as bottom chord which is comprised by top chord by the formation of interconnections at nodes they form pyramids. The proposed methodology is applied to a benchmark space frame structure, yielding significant reductions in weight and improvement structural performance. The improved design shows increased stiffness, strength, and stability, highlighting the success of the proposed method. This research contributes to the development of efficient and sustainable space frame structures, with potential applications in various fields, including aerospace, civil and mechanical engineering. Space frame structures have diverse applications including in buildings, bridges, stadiums, sports tournaments and cultural programs held under one roof. Key considerations in the design process include geometrical constraints, material properties, and the overall structural integrity of the space frame. Indian standards provide the design procedure for space frames, including material properties, load calculations, property assignments, and guidelines for designing steel space frames. The study significantly enhances the performance and material efficiency of space frame structures, providing valuable insights for sustainable engineering practices.

Keywords: double layer grid, structural efficiency and integrity, STADD Pro, optimization space frame structure.

I. INTRODUCTION

The widespread adoption of space frames in recent decades stems from their impressive structural capabilities and aesthetic appeal. Today, space frames are being creatively applied across a broad spectrum of buildings, including. Sports areas, exhibition centers, auditoriums, stadiums, airplane hangars,

workshops, and warehouses. They have been used not only on long-span roofs, but also on mid-and short-span enclosures as roofs, floors, etc. Structural efficiency is crucial in engineering, impacting safety, cost, and sustainability. Space frame structures, widely used in modern construction, can be optimized for enhanced efficiency. This study explores optimization techniques to minimize material usage while maintaining load-carrying capacity, aiming to create sustainable, cost-effective, and resilient space frame structures that advance engineering."

In architecture and structural engineering, a space frame or space structure is a strong, lightweight structure made from interlocking struts in a geometric pattern. Space trusses consist of bars connected by pin joints at nodes. There are two main types of space frame structures based on how the members are connected: the nodular system and the modular system.

In the nodular system, straight truss members are connected through nodes, commonly using the Mero node connector. In the modular system, prefabricated modules are assembled to create the structure. These modules come in various sizes and shapes, offering better aesthetic appeal for the structure.

SPACE FRAME STRUCTURE

A space frame (or space structure) is a lightweight, rigid, three-dimensional structural framework designed to support large spans and heavy loads with minimal material use. It consists of interconnected struts arranged in a geometric pattern. Space frames are used extensively in architectural and engineering projects for roofs, floors, and other structural elements due to their versatility and efficiency.

Because triangles are inherently rigid, a space frame is as stiff as a truss. In space frame structures, bending forces (bending moments) are carried as tension and compression forces along the lengths of individual members. This means that instead of flexing, the frame distributes loads through tension and compression, which stabilizes the structure and makes it highly efficient in bearing loads.

- Optimization of space frame structures has various applications across different industries, including
- Buildings: Space frames are commonly used in large buildings, such as stadiums, airports, exhibition halls, and swimming pools, because they can span large areas with few interior supports.
- Transportation: Space frames are used in high-speed trains and subway vehicles.
- Aerospace: Space frames are used in airplanes and satellites.
- Environmental resilience: Space frames can be designed to collect rainwater, integrate natural lighting, and use sustainable technologies.
- Cost savings: Space frames optimize material usage, which can reduce environmental impact and save money compared to traditional building methods.

Space frames are stable, lightweight structures similar to trusses, composed of interlocking struts arranged in geometric patterns. Their strength lies in the rigidity of triangular shapes, enabling them to support a range of different loads.

Circular hollow sections (CHS) have many advantages, including:

- **Strength and stability:** CHS are strong and stable, making them a good substitute for other steel profiles. The circular shape provides equal strength in all directions, which is beneficial for handling torsion (twisting) and bending. This makes CHS particularly strong under compression and suitable for columns, poles, and trusses.
- **Torsion resistance:** CHS are resistant to large amounts of torsion due to their uniform position around the polar axis.
- **Aesthetic appeal:** CHS have clean lines, a smooth finish, and lack of overhanging edges. The smooth, continuous surface of CHS is often considered visually appealing, especially in architectural designs. It provides a clean and modern appearance, with minimal need for covering or cladding.
- **Lightweight:** CHS are lightweight, which can reduce weight by up to 30%.

II. METHODOLOGY (PART – 1)

PART 1: APSC Existing Space Frame Structure GEOMETRY

The members of a steel space frame are typically straight elements such as bars or struts, and they are connected at their ends to create a stable and rigid structure. The steel space frame is formed double layered grid system with squares and rectangular based pyramids. The plan area on which the space frame rests is of 40m x 40m at height of 10m from ground level. The current space frame consists of a model with square- and rectangular-based pyramids in a two-layer grid system. The bottom grid lies in a single plane, while 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 2m ending the slope to end with the distance of 1.5m in height. Therefore, confirming proper drainage of rainwater from roof.

2 ASSIGNING PROPERTIES OF SECTION

Assign suitable section properties to the beams connecting the two grids based on the design requirements. The space frame is made up of members and connections organized to enable three-dimensional force transfer from the load application point to the supports. The members in the top grid are inclined to drain off the rainwater etc, whereas bottom chord members are straight in a plane at height of 7.25 meters from plinth level 0.65m filling from ground level till plinth level. The distance between top grid and bottom grid at center is 2m and at end it tends to 1.5m 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 210mm outer diameter with thickness of 8mm, whereas inclined members connecting both top and bottom chord members having outer diameter 165 mm with 4.8mm thickness. These steel members or pipes are manufactured through cold rolling to reduce stresses and are seamless to minimize the impact of temperature changes, which can lead to failures like leakage.

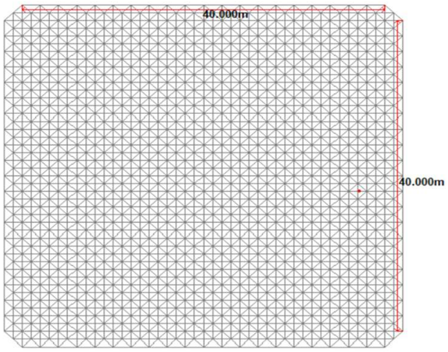

Fig 1 - Plan View of Existing Space Frame; Line Model of APSC

over an Area of 40m x 40m.

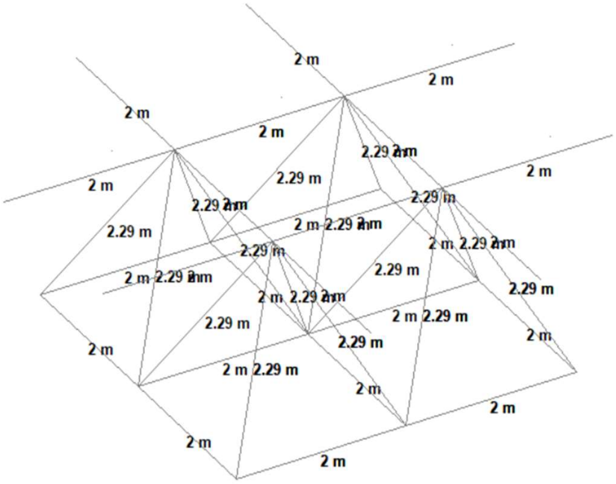

Fig 2 - A Part View of Space Frame Joining Top and Bottom Grid Members.

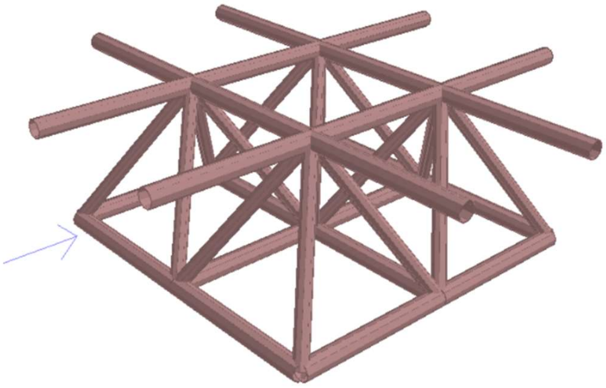

Fig 3 - Rendered View of Space Frame.

SUPPORT CONDITION

The whole steel space frame rests on the entire steel space frame rests on RCC columns positioned around the perimeter, creating a column-free area inside. The columns are spaced 6.5 to 8 meters apart, center-to-center, around the perimeter of the space frame. Each RCC column is connected to beams, forming beam blocks that contain foundation bolts. On these foundation bolts, a 12mm thick MS plate is placed, followed by a 50mm thick neoprene polymer layer (a high-density rubber material), and then another 12mm thick MS plate. Steel pipes are welded to these plates along the perimeter of the structure, allowing the space frame to rest on these plates and be connected to the columns with joints.

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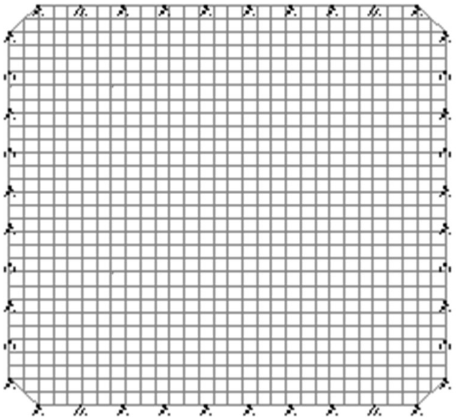

Fig 5 - Bottom Grid Plan with Mesh Size 2m x 2m, with Column Placement.

LOADINGS

The space frame area 40m X 40m, 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 and the height of space frame is 10m from ground level. APSC space frame was so designed for the dead load of cement roofing on space frame, of 50 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/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. 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

ANALYSIS

Finally, the whole structure is analysed in STAADPro.v8i software, with the geometry, properties and loadings discussed above. And check the utility ratio.

1. DISCUSSIONS

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

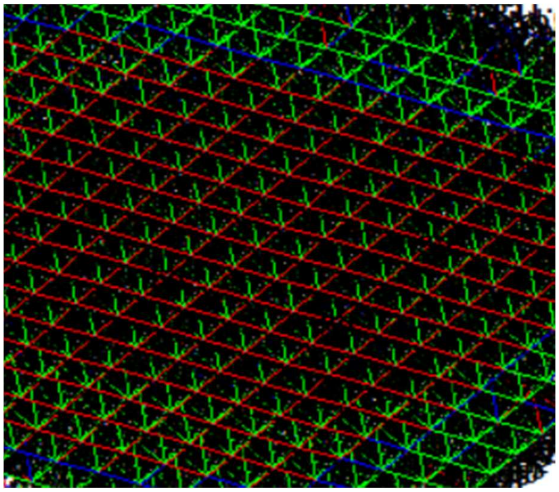

Fig 6 - Utilization Ratios of the Existing Space Frame, After Analysis.

METHODOLOGY (PART – 2)

PART 2: Optimized Space Frame Structure of APSC

GEOMETRY

Based on the analysis of the existing steel space frame structure, we observed that stress distribution is highest at the center and gradually decreases toward the edges. Members of the same length are utilized less efficiently at the periphery, while those at the center exhibit higher utilization ratios. Conceptually, this can be visualized as the top and bottom grid members having maximum depth at the center, which progressively decreases toward the edges. This results in a dome-like shape for the top grid, while the bottom grid members remain in the same plane.

2 ACCUMULATIONS OF STRUCTURE

The above concept is made to give a proper flow to rainwater for drainage, and 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 consist of the mesh of 2m x 2m, 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.

S.NO	GRID WITH MESH	Mesh size
1	Top Grid	2m×2m
2	Bottom Grid	2m×2m

Table 2 - Geometry of Optimized Space Frame

S.NO	Member	Property	OD	Thickness	YST (Mpa)	UST (Mpa)
1	Top Grid	CHS	219mm	8mm	310	450
2	Bottom Grid	CHS	219mm	8mm	310	450
3	Inclined Grid	CHS	165mm	4.5mm	310	450

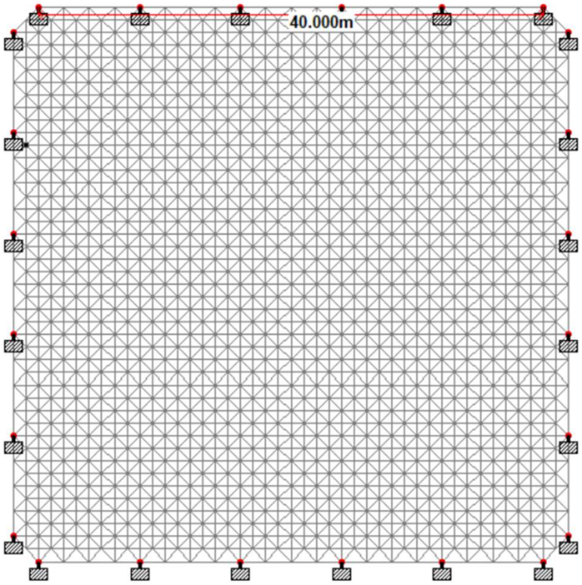

Fig 8 - Optimized Space Frame Model of APSC

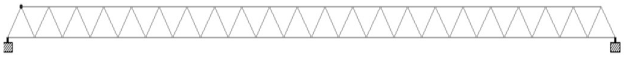

Fig 9 - Sectional Elevation of Optimized Space Frame

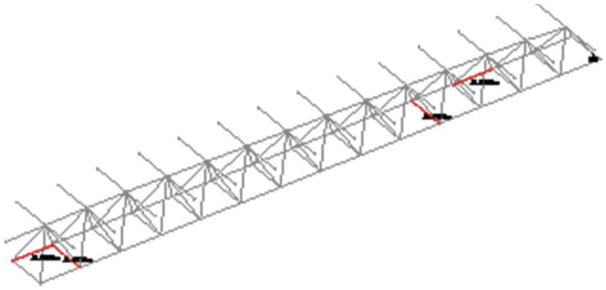

Fig 10 - Elevation View of Optimized Space Frame Showing Slope

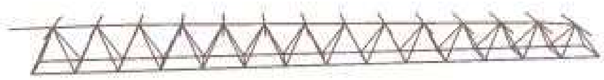

Fig 11 - Rendered Elevation View of Optimized Space Frame with Top Grid Slope

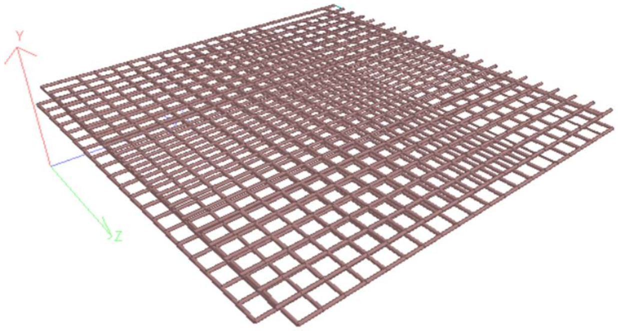

Fig 12 - Rendered Elevation View of Optimized Space Frame of top and bottom grid

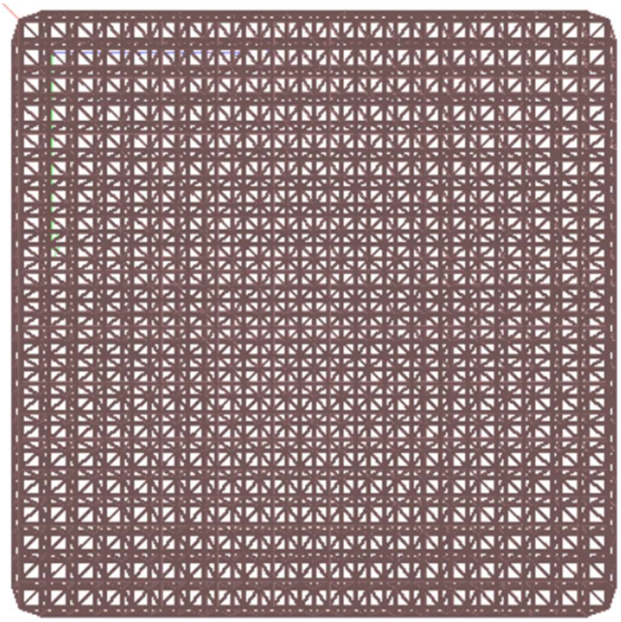

Fig 13 - Rendered View of Optimized Space Frame of APSC

SUPPORT CONDITION

The support condition of the optimized space frame is 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 8 meters Centre to Centre at the periphery of space frame.

4.2 DESIGN SPECIFICATION (as per IS 800:2007)

4.2.1 MATERIAL

All structural steel used in the construction of the space frame undergoes inspection before fabrication and complies with the IS 2062 standard. These specifications are also detailed in IS 800:2007, Table 1 (Page 14), with a yield strength of 310 MPa and an ultimate strength of 450 MPa.

4.2.2 OBJECTIVE

The goal of the design is to ensure the structure remains safe and functional throughout its intended lifespan. By applying appropriate safety factors, the design should minimize deformations and withstand all anticipated loads during and after construction. It must also resist accidental loads and avoid sudden collapse, providing sufficient warning under any critical condition.

4.3 METHOD OF DESIGN

The structure is designed using the Limit State Method as per IS 800:2007, which integrates theoretical analysis, experimental data, and practical experience.

2 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, Table1, 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 considers of theories, experiments and experience.

SECTIONAL PROPERTIES

- Area of cross- section A = $\frac{\pi}{4}(OD^2 - d^2)$
- Moment of Inertia I_{xx} I_{yy} = $(OD^4 - d^4)$ = Elastic section modulus Z= $\frac{\pi}{32\times OD}(OD^4 - d^4)$
- Plastic section modulus Z = $(OD^3 - d^3)/6$
- Radius of Gyration r_{xx} $r_y = \sqrt{\frac{I}{A}}$

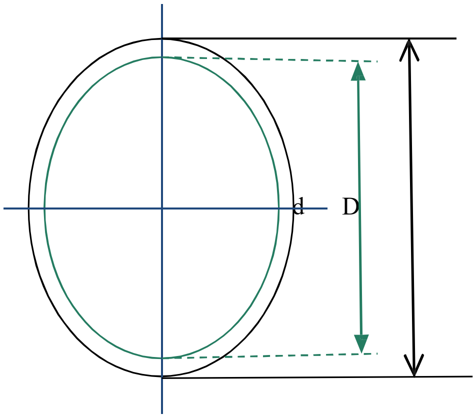

Fig Cross section of Hallow Circular section

CLASSIFICATION OF SECTIONS

Sections are classified based on their moment-rotation capacity as follows:

1. Plastic (Class 1) Sections: These sections can develop plastic hinges and have the necessary rotation capacity to allow the structure to fail through the formation of a plastic mechanism

2. Compact (Class 2) Sections: These sections can develop the plastic moment of resistance (Mp) but lack sufficient rotation capacity for plastic hinge formation due to local buckling.

3. Semi-Compact (Class 3) Sections: These sections can reach the yield stress at the extreme fiber compressive stress but cannot develop the plastic moment of resistance due to local buckling.

4. Slender (Class 4) Sections: These sections experience local buckling of plate elements before the extreme fiber compressive stress reaches the yield stress.

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

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)

CALCULATION OF LOADS

Load Calculations (As per IS 800:2007)

Dead load on frame structure

Self-weight of structure

Assume Weight of A.C sheets =120 N/mm^2

Weight of purlins = 100 N/mm^2

Total dead load = 183.33+120+100 = 403.3 N/m^2

= 0.403×2 = 0.803 KN/ m^2

Live load on frame structure

Access not provided = 750 N/m^2 (As per IS 875-Part (2)

Live load on rafter = 0.75 KN/m^2

Wind load on frame structure

- Design Wind Speed (V_Z):

1. Basic wind speed V_b is taken from the map of India given in IS 875-1987 (See Fig. 6.6) and Table 6.2

2. The basic wind speed is modified (V_Z) by taking constants k_2 and k_3, k_l

V_Z= Design wind speed (m / s) at any height z above ground

V_b = Basic wind speed

K_l= probability factor or risk co-efficient

K_2 = terrain, height, structure, size factor

K_3 = topography factor

K_4 = Importance factor for cyclonic region

$$\mathbf{V_Z = V_b \times k_1 \times k_2 \times k_3 \times k_4}$$

RISK CO-EFFICIENT (K)

Table 6.3 gives the values of Risk Coefficient (k_l) for basic wind speed (m / s) for terrain category 3 as applicable at 10 m above ground level, based on 50 years life.

K_l = 1.0 (As per IS 875(Part-3)-2015: Table 1, Clause No 6.3.1

K_2 = 0.91 (For terrain category 3 and for height = 10m (Clause No 6.3.2)

K_3 = 1.0 (As per IS 875 (Part-3)-2015: Table 2 (Clause No 6.3.3)

K_4 = 1.0 ((As per IS 875 (Part-3)-2015: Clause No 6.3.4)

V_b = 47m/sec

Substitute in above equation

V_Z = 47×1.0×0.91×1.0×1.0 = 42.77m/sec

Design Wind Pressure Calculation

$$\mathbf{P_d = k_a + k_d + k_c + P_Z > 0.7P_Z}$$

[from is 875 (part3): 2015 page No-8, Clause No. 7.3]

Area averaging factor k_a = 0.85 (clause 7.2.2, Table -4)

Wind directionality factor, k_d= 1.0, (clause 7.2.1)

Combination factor, k_c = 0.9 (clause 7.3.3.13)

Wind pressure at height at Z in N/m²

$$\mathbf{P_Z = 0.6V_Z^2}$$

$P_z = 0.6(42.77)^2 = 1097.563$

$P_d = k_d * k_c * k_a * 1097.563$

k_d = 1.0 for Circular section (Clause No 7.2)

k_c = 0.85 (Clause No 7.2.1)

k_a = 0.9 (Clause No 7.3.3.13)

ka* ka* kc ≥ 0.7 = 1 * 0.85 * 0.9 ≥ 0.7

$0.765 \geq 0.7$ Hence ok

$P_d = 0.765 \times 1097.563 = 839.63\,N/m^2 = 840\,N/m^2$

$P_d = 0.84\,kN/m^2$ (wind Intensity)

opening % = open Area / Total Area = 0.04/1.6

0.030 (or) 0.028% (Permeability up to 5% to 20%)

Internal pressure Coefficient Cpi = ±0.5

Hance the frame is of medium permeability

IS 875 part-3 7.3.2-2]-2015

External pressure Coefficient:

Using the table-6 h=10m W=40m without root angle 0^0

$\frac{h}{w} = 10/40 = 0.25 < (0.5)$ without local coefficient for $\frac{h}{w} = 0.5$

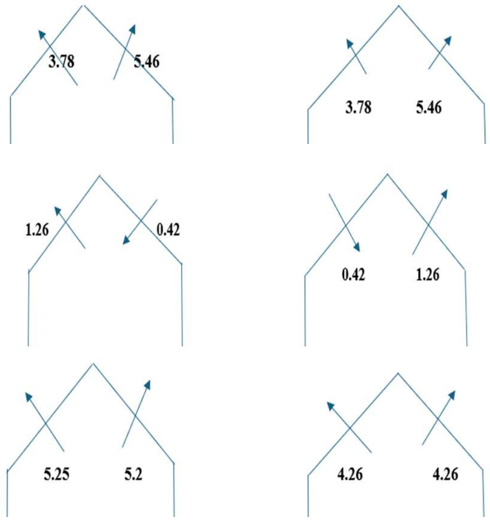

Fig - Wind Internal and External Pressure Coefficient of Roof

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)

Tension Members Tension members are linear structural elements that experience axial forces causing them to elongate or stretch. These members can support loads up to their ultimate load limit, beyond which they may fail due to rupture at a critical section. However, if the gross area (the total cross-sectional area) of the member begins to yield significantly along its length before reaching the rupture load, the member may lose its functionality due to excessive elongation. Additionally, plates and other rolled sections under tension may also fail through block shear in areas with end bolting (see 6.4.1).Design Strength Due to Yielding of Gross Section The design strength, , of members subjected to axial tension is determined by the yielding of the gross section. This defines the maximum strength the member can sustain before yielding.

B. COMPRESSION (Section 7)

Section 7 focuses on the design of compression members, addressing parameters such as the non-dimensional effective slenderness ratio, imperfection factor, and effective slenderness ratio. According to Table-10, hollow sections fall under buckling class "a," indicating that they offer the highest resistance to buckling. By following the design procedure outlined in IS800:2007, the compressive strength of the member can be calculated.

C. ENDING AND SHEAR (Section 8)

According to Clause 8.2.2, the code specifies that hollow sections are classified as laterally supported members, meaning they are not susceptible to lateral-torsional buckling failure. The bending strength of such members is assessed as described in Clause 8.2.1.2 for laterally supported members. Additionally, the section must be evaluated for both low and high shear as per Clause 8.4. For hollow sections, the shear-resisting area is defined as , which represents the area capable of resisting shear forces. The shear capacity is then calculated based on this criterion.

D. COMBINED ACTIONS (Section 9)

There are two types of combined actions:-

1- Compression + Bending

2- Tension + Bending

To verify the member's performance under combined actions, two criteria were considered: the sectional strength, ensuring the cross-section does not fail due to local effects, and the overall strength, ensuring the member withstands external loads, buckling, and similar factors. Based on these considerations, an Excel sheet was developed to evaluate all the design parameters as per IS

800:2007. The results were then cross verified with the STAAD model outputs and manual calculations.

RESULTS

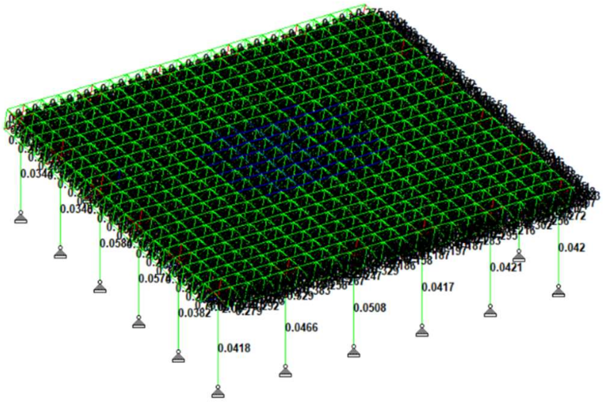

Fig 17c - Utilization Ratios of Optimized Space Frame Structure, After Analysis.

CONCLUSION AND DISCUSSION

. The utilization of space frame structure figure illustrates the utilization ratios of the optimized steel space frame structure. Notably, the green-coloured regions exhibit high utilization (0.67), indicating optimal member utilization. It is clear from this study that we are improving the space frame of the previous one.

In this study presents a comprehensive optimization approach for space frame structures, aiming to minimize structural failure while maintaining structural integrity.

The design and optimization of space frames involves advanced mathematical techniques and software tool to analyse various design parameters, such as geometry, material properties, and load conditions.

Key Findings:

- Reducing member size increases utilization.
- Increasing mesh size enhances utilization of inclined members.
- Top grid members at the center are more utilized (purple) compared to peripheral
- Grid members.

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