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Analytical Investigation on Bio-Inspired Long-Span Steel Roof Truss for an Airport Terminal

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Abstract - The design of long-span airport roof structures demands high structural efficiency, reduced self-weight, and superior performance under complex loading conditions. Conventional steel trusses are often limited by linear load paths and inefficient stress distribution, restricting their effectiveness in large spans. This study proposes a novel bio-inspired steel truss system based on spider-web geometry, enabling multi-directional load transfer and enhanced structural redundancy. A 114 m span roof structure is developed using parametric modeling and evaluated through finite element analysis (FEA). The system integrates radial and circumferential members to replicate natural force-flow mechanisms, resulting in optimized stress distribution and improved load transfer efficiency. Structural analysis includes linear static analysis for deflection and stress evaluation, buckling analysis for global and member stability, and modal analysis to assess dynamic response and natural frequencies. The model is subjected to dead, live, and wind loads as per IS 875, with design verification based on IS 800:2007.A comparative study with a conventional Pratt truss reveals notable improvements in stiffness-to-weight ratio, buckling resistance, vibration performance, and overall material efficiency. The findings establish biomimicry as a high-performance, resilient, and sustainable solution for next-generation long-span structures.

Keywords -Biomimicry, long-span truss, spider-web structure, Finte element analysis, structural optimization.

I. INTRODUCTION

Airport terminal buildings represent a class of structures where long-span roofing systems are essential to ensure uninterrupted functional space and architectural openness. The requirement for large column-free areas introduces significant challenges in structural design, particularly in terms of load transfer, serviceability, and material optimization. As span length increases, issues such as excessive deflection, stability, and dynamic response become more critical and often govern the design.

Steel truss systems are commonly employed in such applications due to their high strength-to-weight ratio, modular construction, and adaptability to various geometric configurations. These systems primarily resist loads through axial action in members, making them efficient for long-span applications. However, conventional truss arrangements, which are typically based on repetitive linear geometries, may not always achieve optimal structural efficiency. In many cases, they result in non-uniform stress distribution, increased self-weight, and limited redundancy, especially under complex loading conditions such as wind-induced effects.

To address these limitations, bio-inspired design approaches have been explored in recent structural engineering research. Biomimicry involves the abstraction and application of natural structural principles to engineered systems. Natural forms have evolved over time to achieve highly efficient load-bearing mechanisms with minimal material usage. These systems often exhibit characteristics such as hierarchical organization, multi-load-path redundancy, and enhanced adaptability.

Among various natural systems, spider webs present a particularly effective structural model due to their ability to sustain external forces through a network of radial and circumferential elements. The geometry enables efficient stress redistribution and provides inherent redundancy, allowing the structure to maintain integrity even in the event of localized damage. The combination of tensile load resistance, flexibility, and energy dissipation makes spider-web configurations a promising candidate for long-span structural applications.

In this context, the present study investigates the feasibility of adopting a spider-web-inspired geometry for long-span steel roof trusses in airport terminals. The work focuses on the analytical evaluation of structural behavior, including load distribution, deflection characteristics, stiffness requirements, and overall efficiency. The objective is to assess whether such a bio-inspired configuration can provide a viable and improved

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alternative to conventional truss systems for large-span infrastructure.

I. *Problem Statement*

Designing long-span roof systems for airport terminals involves several structural challenges, primarily due to the requirement of large column-free spaces that ensure smooth passenger movement and operational efficiency. These systems must be lightweight while maintaining sufficient strength, making structural optimization a key concern. In addition, serviceability criteria such as deflection and vibration control become critical, especially for larger spans where these factors often govern the design.

Conventional steel truss systems are widely used for such applications; however, they may not always provide optimal performance. They often involve higher material consumption and offer limited alternative load paths, which reduces redundancy and efficiency under complex loading conditions. Furthermore, traditional truss geometries may not be well-suited for modern architectural demands.

In this context, the present study explores the application of a spider-web-inspired truss system, aiming to evaluate its structural behavior and address the existing gap in analytical research for large-scale bio-inspired structures.

II. *Objectives*

The primary objective of this study is to investigate the applicability of bio-inspired structural systems by developing a spider-web-based truss configuration for long-span roof applications.
A parametric geometric model of the proposed system is generated and subsequently converted into a finite element model for detailed analysis. The study aims to evaluate the structural response under applied loading conditions, including dead, live, and wind loads, using finite element analysis techniques.
Further, the work focuses on assessing key performance parameters such as nodal displacements, member axial forces, stress distribution, and global stiffness characteristics.
Stability analysis is carried out through buckling evaluation, while dynamic behavior is examined using modal analysis to determine natural frequencies. Based on these results, the feasibility and structural efficiency of the proposed bio-inspired truss system are critically assessed in comparison with conventional design approaches.

III. LITERATURE REVIEW

The application of bio-inspired concepts in structural engineering has gained increasing attention over the past decade, particularly in the design of efficient and lightweight long-span systems.

Studies on biomimicry in structural systems indicate that natural forms such as honeycombs, tree branches, and spider webs exhibit highly optimized geometries that enhance load distribution and structural resilience. These systems are characterized by their ability to transfer loads through multiple interconnected paths, reducing stress concentration and improving overall stability.

Research on long-span steel truss systems highlights that structural efficiency is often governed by stiffness-to-weight ratio and effective load path mechanisms. Conventional truss configurations, while effective, may experience limitations in terms of material optimization and adaptability to complex architectural requirements. Several researchers have suggested that non-conventional geometries can improve performance by redistributing internal forces more effectively.

Analytical investigations on bio-inspired geometries have shown that spider-web-like configurations provide improved redundancy and resistance to progressive collapse. The presence of radial and circumferential members allows the structure to redistribute loads in case of localized failure, thereby enhancing safety. In addition, such geometries have been observed to delay buckling and improve overall stability under dynamic loading conditions.

Finite Element Analysis (FEA)-based studies further indicate that bio-inspired structures can achieve significant improvements in performance metrics. Reported findings include reductions in mid-span deflection by approximately 15–20% and material savings in the range of 10–25%, depending on the level of optimization. Furthermore, nodal configurations inspired by natural branching systems have been shown to reduce stress concentration and improve fatigue performance.

In the context of airport terminal structures, long-span roof systems are subjected to complex loading conditions, including wind, temperature variations, and dynamic effects. Literature suggests that integrating bio-inspired geometries with advanced computational tools such as parametric modeling and FEM can lead to more efficient and adaptable structural solutions.

IV. METHODOLOGY

The methodology adopted in this study involves a systematic approach combining parametric modeling and finite element analysis to evaluate the performance of the proposed bio-inspired truss system.

i. Concept Selection and Geometry Development:
A spider-web-inspired structural configuration is selected based on its efficient load distribution characteristics. The geometry is developed using parametric modeling tools such as Rhino and Grasshopper to generate radial and circumferential member arrangements.

ii. Finite Element Model Generation:
The developed geometry is imported into finite element software, where the structure is discretized into appropriate elements. Material properties corresponding to structural steel (Fe 345 / S355) are assigned, and suitable cross-sectional properties are defined.

iii. Boundary Conditions and Connectivity:
Support conditions are applied based on realistic structural behavior, typically considering pinned and roller supports at column locations. Proper connectivity between radial and ring members is ensured to simulate actual load transfer mechanisms.

iv. Load Application:
Loads including dead load (self-weight), live load, and wind load are applied in accordance with IS 875 provisions. Relevant load combinations are considered to evaluate critical structural responses.

v. Structural Analysis:
Linear static analysis is performed to obtain nodal displacements, member forces, and stress distribution. Buckling analysis is carried out to determine stability and critical load factors. Modal analysis is conducted to evaluate natural frequencies and dynamic characteristics.

vi. Result Evaluation:
The results are analyzed with respect to serviceability criteria such as deflection limits and strength requirements. Key parameters including stiffness, stability, and load distribution are assessed.

vii. Comparative Assessment:
The performance of the bio-inspired truss system is compared with a conventional truss configuration of similar span and loading conditions to evaluate improvements in efficiency and behavior.

V. CONCEPTUAL MODELING

Spider-web geometry consists of a network of radial members connected by concentric rings, forming an interconnected structural system. This configuration enables efficient load transfer through multiple load paths, reducing stress concentration and improving structural redundancy.

The radial members primarily resist tensile forces, while the circumferential elements help in redistributing loads and enhancing stability. One of the key advantages of this system is its ability to maintain structural integrity even in the case of localized failure, as loads can be redistributed through alternate paths.

From a structural perspective, such geometries exhibit improved stiffness-to-weight characteristics and enhanced energy dissipation under dynamic loading conditions. These features make spider-web-inspired systems a promising option for long-span applications such as airport terminal roofs.

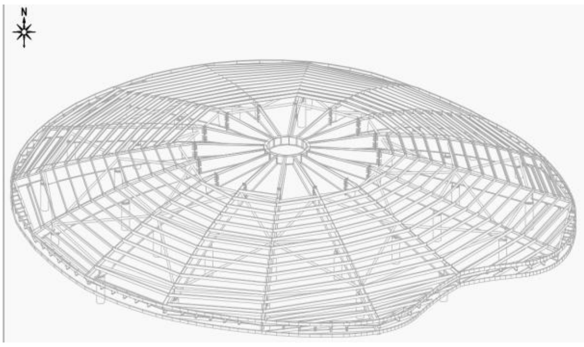

Fig 1.3D Parametric modelling of spiderweb roof truss.

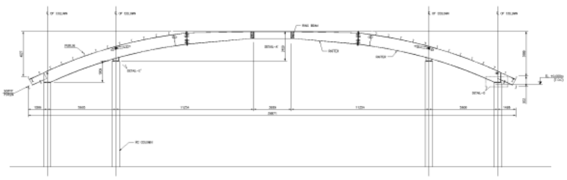

Fig 2. Section of spiderweb roof truss.

VI. ANALYTICAL EVALUATION

The analytical evaluation examines the structural behavior of the spider-web-inspired truss system under applied loading conditions. The study focuses on key performance parameters such as load distribution, stiffness, deflection, stability, and dynamic response. Results indicate efficient load transfer and improved redundancy due to multiple load paths. However, deflection is identified as the governing criterion, highlighting the need for stiffness enhancement. The evaluation provides insights into the feasibility and performance limitations of the proposed system for long-span airport roof applications.

I. Structural Idealization and Loading

The spider-web-inspired roof structure is idealized as a network of radial and circumferential members forming an interconnected truss system. The loading is assumed to be uniformly distributed over the roof surface and is transferred to the structural system through radial members.

The total load acting on the structure is expressed as:

$W=q.A=q.\pi R^2$

where:

q = uniformly distributed load (N/m²)

R = radius of the structure (m)

The load carried by each radial member is approximated as:

$$W_r=q.\pi R^2 N_r$$

where Nr is the number of radial members.

II. *Axial Stiffness and Load Transfer Behavior*

The structural response is governed primarily by axial forces in the members. The axial stiffness of each member is given by:

$$k=EA/L$$

where:

E = Young's modulus of steel

A = cross-sectional area

L = member length

Due to the interconnected geometry, the structure provides multiple load paths, allowing efficient force redistribution and improving redundancy.

III. Deflection and Serviceability Response

Deflection is identified as the governing parameter for long-span structures. The maximum deflection under uniformly distributed load is given by:

$$\delta = (5 w L^4) / (384 E I)$$

The allowable deflection is generally limited to:

$$\delta\_allow = L/200 \text{ to } L/250$$

The calculated deflection exceeds permissible limits, indicating insufficient stiffness.

IV. Stability and Buckling Performance

The stability of compression members is evaluated using Euler's buckling equation:

$$P_{cr} = (\pi^2 E I) / (K L)^2$$

where Pcr is the critical load and K is the effective length factor.

The structure is stable under moderate loading, but slenderness effects must be considered.

V. Dynamic Characteristics

The dynamic response is evaluated using the fundamental natural frequency:

$$f = (1 / 2\pi) \sqrt{(k / m)}$$

A lower natural frequency indicates higher sensitivity to dynamic effects such as wind.

VI. Design Implications and Required Modifications

The analytical evaluation indicates that although the spider-web geometry enhances load distribution, stiffness remains the governing design factor. To satisfy serviceability requirements, the required moment of inertia can be increased using:

I $$I \propto (w L^4) / (E \delta_{allow})$$

This indicates that increasing stiffness through greater depth, additional members, or secondary

support systems is necessary for improving performance.
This suggests that increasing member depth, adopting a double-layer truss system, or introducing ring supports can significantly improve structural performance.

VII. FEM RESULTS AND INTERPRETATION

The finite element analysis of the spider-web-inspired truss system was carried out to evaluate its structural performance under applied loading conditions. The results indicate that maximum displacement occurs at the mid-span region, with deflection exceeding permissible serviceability limits. This confirms that stiffness is the governing design criterion for the proposed system.

The stress distribution shows effective load transfer through both radial and circumferential members, ensuring uniform force flow and reducing stress concentration. Axial force results indicate that members primarily carry tension and compression, demonstrating efficient truss action.

Buckling analysis reveals that the structure is stable under the given loading conditions, although slender members may require additional consideration. Modal analysis indicates a relatively low natural frequency, suggesting sensitivity to dynamic effects.

VIII. COMPARATIVE ANALYSIS AND DESIGN IMPLICATIONS

A comparative study was carried out between the bio-inspired spider-web truss and a conventional steel truss of similar span and loading conditions. The results indicate that the bio-inspired configuration provides improved load distribution due to the presence of multiple load paths. However, it exhibits higher deflection due to reduced stiffness. The conventional truss shows better control over deflection but lacks redundancy in load transfer. The bio-inspired system, on the other hand, demonstrates enhanced structural resilience and potential for material optimization.

The results highlight that stiffness is the governing factor in the design of long-span bio-inspired structures. While the geometry improves load distribution, additional measures such as increased truss depth, use of double-layer systems, or incorporation of ring supports are required to control deflection.

IX. CONCLUSION

The present study investigates the feasibility of a bio-inspired spider-web truss system for airport terminal roofs. The results indicate that the proposed configuration offers improved load distribution and redundancy.

However, deflection is identified as the governing design factor, requiring further optimization. The study provides a foundation for future work in the development of efficient and sustainable long-span structural systems using bio-inspired concepts.

X. FUTURE SCOPE

Further work can focus on detailed finite element analysis and optimization of the geometry. Experimental validation may be carried out to verify analytical results.The integration of advanced optimization techniques and hybrid structural systems can further improve performance. The concept can also be extended to other large-span structures.

REFERNCES

[1] G. Akcaer and A. Soyluk, “Effect on the dynamic behaviour of the form in airport terminal constructions with biomimetic roof,” International Journal of Space Structures, 2018.
[2] H. Zhang, Y. Li, and X. Chen, “Spider web geometry inspires long span roof trusses,” Massachusetts Institute of Technology, Thesis, 2020.
[3] J. Li, Y. Zhang, H. Wang, and P. Sun, “Exploration of the design of spiderweb-inspired structures for large-area sensing and mechanics,” PMC, 2023.
[4] J. Feng, Y. Liu, and Z. Wang, “Form-finding and shape optimization of bio-inspired branching structures,” Structural Optimization Journal, 2020.
[5] Y. Yang, H. Du, G. Yao, X. Ma, and W. Men, “Design for robustness: Bio-inspired perspectives in structural engineering,” Biomimetics, vol. 8, no. 5, p. 145, 2023.

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DOI: https://doi.org/10.64388/IREV9I10-1717049

[6] Q. Li, T. Zhang, and S. Wang, "Layout optimization of long-span structures subject to self-weight and multiple load cases," Structural Optimization Journal, 2022.
[7] X. Chen, H. Zhou, and L. Sun, "Topology, size and shape optimization in civil engineering — A review," Automation in Construction, vol. 155, p. 104110, 2024.
[8] W. Zhang, H. Liu, and J. Peng, "Topology optimization algorithm for spatial truss based on numerical inverse hanging method," Engineering Structures, vol. 301, p. 115447, 2024.
[9] Y. Wang, Z. Liu, and X. Zhou, "Size, shape and topology optimization of truss structure via the finite point method," Journal of Constructional Steel Research, vol. 204, p. 107788, 2024.
[10] X. Zhao, S. Li, and H. Tang, "Rapid mechanical property prediction and de-novo design of spider-web microstructures," Nature Communications, vol. 13, p. 2214, 2022.
[11] A. Rossi, M. Bianchi, and F. Verdi, "FEM analysis of spider-web inspired structures," Politecnico di Milano, Thesis, 2013.
[12] Y. Zhang, H. Chen, and M. Liu, "Bio-inspired thin-walled straight and tapered tubes with variable designs," Buildings, vol. 13, no. 6, p. 1551, 2025.
[13] H. Sahu and R. Satbhaiya, "Structure optimization assessment for steel truss," IJSRCE, vol. 11, no. 4, pp. 102–115, 2023.
[14] J. Feng, Y. Liu, and Z. Wang, "Design optimization of trusses based on structural mechanics mechanisms," EWA Proceedings, 2024.
[15] P. Ahiwale and P. Khartode, "Parametric study for long-span roof truss subjected to vertical ground motion," Springer, 2021.