Comparative Dynamic Analysis of Stadium Roof Structures With Varying Geometrical Forms

Mr. Abhishek S. Nawghare[1], Dr. Swati Ambadkar[2]
[1]*Student M. Tech. (Structural Engg.) Dept. of Civil Engineering, G. H. Raisoni University, Amaravati, Maharashtra, India*
[2]*Associate Professor, Dept. of Civil Engineering, G.H.Raisoni University, Amaravati, Maharashtra, India*
[1]abhisheknawghare2001@gmail.com

Abstract— Stadium roof structures are among the most challenging and functionally critical components in modern sports facilities due to their large spans, complex geometrical forms, and vulnerability to dynamic loading. The present study focuses on a comparative dynamic analysis of stadium roof structures with varying geometrical forms. Tubular roof systems are designed in accordance with IS 801:2005, ensuring code based compliance in member sizing and detailing. Multiple roof geometries such as dome-shaped, radial truss, and asymmetric configurations are modelled in STAAD-Pro and subjected to dynamic analyses using selected recorded earthquake ground motions. Time-history analysis is employed to capture displacement response, internal member forces, natural frequencies, and modal behaviour. Post-dynamic performance of the structures is evaluated in terms of structural safety, serviceability, and energy dissipation characteristics. Analytical validation through simplified methods is carried out to cross-check and confirm the accuracy of STAAD-Pro results. The comparative findings highlight the influence of roof geometry on dynamic response and provide recommendations for selecting geometrical forms that enhance seismic performance while maintaining structural efficiency.

Keywords: *Stadium roof structures, Dynamic analysis, Tubular truss, Earthquake ground motion, STAAD-Pro*

I. INTRODUCTION

A stadium roof is a roof system designed to roll back the roof on tracks so that the interior of the facility is open to the outdoors. Retractable roofs are sometimes referred to as operable roofs or retractable skylights. The term operable skylight, while quite similar, refers to a skylight that opens on a hinge, rather than on a track. Stadium roofs are used in residences, restaurants and bars, swim centers, and other facilities wishing to provide an open-air experience at the push of a button.

Stadiums are iconic structures that represent not only engineering excellence but also architectural innovation. Among their various components, the roof system plays a crucial role in ensuring both functional and structural performance. Unlike conventional building roofs, stadium roofs typically span large areas, adopt complex geometrical forms, and are required to provide unobstructed visibility, weather protection, and long-term durability. These demands make them structurally more vulnerable to dynamic actions such as wind and earthquake loading.

Dynamic analysis of stadium roof structures is essential for understanding their behaviour under seismic ground motions. The geometry of the roof strongly influences parameters such as stiffness, natural frequency, and load distribution. Tubular truss systems are widely adopted in long-span structures because of their light weight, high strength-to-weight ratio, and architectural versatility. However, their behaviour under real earthquake excitations varies significantly with roof form, making comparative analysis an important research need.

A. Types Of Stadium Roofs

Stadium roofs are a critical component of modern sports architecture, providing shelter, comfort, and aesthetic appeal while maintaining visibility and acoustics. The choice of roof type depends on various factors such as climate conditions, structural efficiency, cost, architectural design, and intended use of the stadium. Roof systems in stadiums are designed to cover large spans without obstructing spectators' views and to resist environmental loads like wind, rain, and seismic activity. Modern stadiums use advanced materials such as steel, tensile membranes, ETFE (ethylene tetrafluoroethylene), and composite structures, ensuring lightweight yet durable performance. Below are the major types of stadium roofs used worldwide.

Fixed Roof

A permanent, rigid structure covering the entire stadium or spectator areas. It is non-movable and designed for complete weather protection.

Retractable Roof

A movable roof that can open or close depending on weather or event requirements. Operated mechanically through sliding panels or folding systems.

 ISSN: 3107-6513

Cantilever Roof

A roof supported only on one side by beams or columns, projecting outward to cover the stands without internal supports that block views.

Cable-Supported Roof

A system of steel cables in tension that supports the roof membrane or panels over a large span.

Dome Roof

A curved or spherical roof structure that evenly distributes loads to the supports.

II. PROBLEM STATEMENT

Stadium roof structures with large spans are highly sensitive to seismic effects, and their performance largely depends on geometry. Tubular roof systems, while efficient, show complex dynamic behavior under earthquake ground motions. Existing studies focus more on software analysis without adequate validation through analytical methods. A comparative dynamic study of varying geometrical roof forms is needed to assess post-dynamic behavior, validate STAAD-PRO results, and provide reliable design insights for safer and more economical stadium roofs.

3 Models Are Compared In This Project Subjected To El-Centro Data

- Type-1 Flat Stadium Roof
- Type-2 Curved Stadium Roof
- Type-3 Inclined Roof

[1] Type-1 Flat Stadium Roof

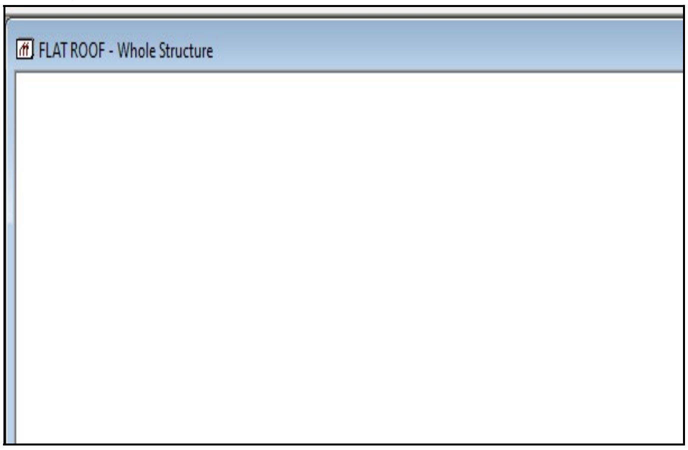


Fig 1 Flat Roof

[2] Type-2 Curved Stadium Roof

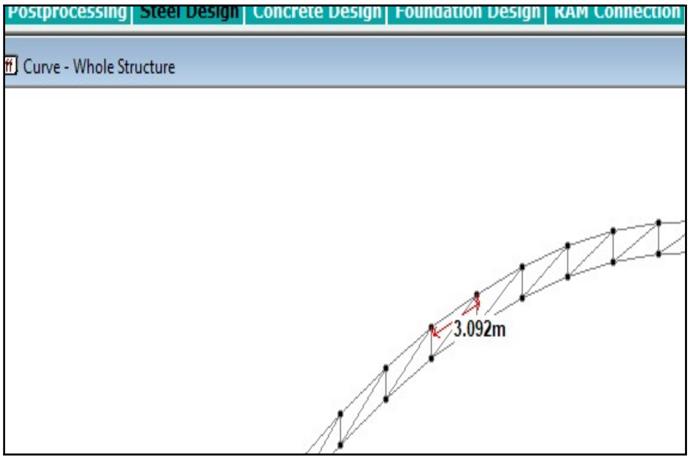


Fig 2 Curved Roof

[3] Type-3 Inclined Roof

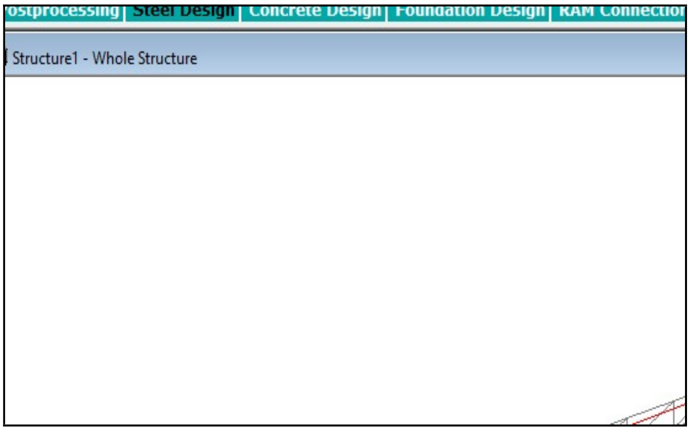


Fig 3 Inclined Roof

III. METHODOLOGY

3.1 Structural Models

In the present study, three different stadium roof configurations were modeled and analyzed using STAAD.Pro Official Website software to evaluate their structural and dynamic performance under wind and seismic loading conditions. All roof systems were modeled as double-layer space truss structures using circular hollow steel sections. The selected roof geometries were intended to represent commonly adopted long-span stadium roof forms in modern structural engineering practice.

a) Type 1 – Flat Roof

The first model consists of a flat double-layer space truss roof having a horizontal roof profile. The roof geometry does not contain any curvature or inclination, resulting in a comparatively stiffer structural system. The flat roof was selected as the reference model for comparing the behavior of other roof geometries.

b) Type 2 – Inclined Roof

The second model consists of an inclined double-layer space truss roof with an inclination angle of 18.5°. The inclined

 ISSN: 3107-6513

geometry provides improved drainage and architectural appearance; however, it introduces additional lateral components of forces and changes the stiffness characteristics of the structure under dynamic loading.

c) Type 3 – Curved Roof

The third model consists of a parabolic curved roof with a central rise of 15 m. The curved profile improves aerodynamic behavior and enhances load distribution throughout the structure. Due to its arching action and geometrical configuration, the curved roof is expected to perform better under wind and seismic excitation.

All three models were developed with identical plan dimensions and structural properties to ensure a fair comparative analysis. The only varying parameter among the models was the roof geometry.

3.2 Geometrical Details

The geometrical and structural parameters adopted for the numerical modeling are presented in Table 3.1.

Table 3.1 Geometrical Details of Stadium Roof Models

Parameter	Flat Roof	Inclined Roof	Curved Roof
Structural System	Double Layer Space Truss	Double Layer Space Truss	Double Layer Space Truss
Plan Length	60 m	60 m	60 m
Structural Depth	1.5 m	1.5 m	1.5 m
Panel Spacing	3 m	3 m	3 m
Roof Geometry	Flat	Inclined	Parabolic Curved
Inclination Angle	0°	18.5°	Not Applicable
Rise Height	0 m	20.04 m	15 m
Material	Structural Steel	Structural Steel	Structural Steel
Section Used	60.3 × 2.9 mm CHS	60.3 × 2.9 mm CHS	60.3 × 2.9 mm CHS
Seismic Zone	Zone III	Zone III	Zone III
Analysis Type	Linear Static & Dynamic	Linear Static & Dynamic	Linear Static & Dynamic

The models were generated using beam elements in STAAD.Pro and discretized at regular intervals of 3 m panel spacing to achieve accurate finite element representation.

3.3 Material Properties

Structural steel was used as the primary construction material for all roof models due to its high strength-to-weight ratio, ductility, and suitability for long-span structures. The material properties were assigned according to relevant Indian Standard provisions.

d) Table 3.2 Material Properties of Structural Steel

Property	Value
Unit Weight	76.97 kN/m^3
Modulus of Elasticity (E)	2.5×10^5 MPa
Poisson's Ratio	0.30
Yield Strength (Fy)	415 MPa
Tensile Strength (Fu)	485 MPa
Shear Modulus	76,923 MPa
Thermal Coefficient	1.17×10^{-6} /°C

Circular Hollow Sections (CHS) of size 60.3 × 2.9 mm were initially selected for all truss members because of their efficient torsional behavior, reduced wind resistance, and aesthetic appearance suitable for stadium roof applications.

3.4 Loading Conditions

The structural models were analyzed under different loading conditions to evaluate their behavior under static and dynamic actions. The loading conditions were assigned according to relevant Indian Standard codes.

The following load cases were considered:

- Dead Load (DL)
- Wind Load (WL)
- Response Spectrum Load
- Time History Seismic Load using El-Centro Earthquake Data

e) Dead Load

Dead load consisted of the self-weight of structural members automatically calculated by STAAD.Pro software based on material density and sectional properties.

f) Wind Load

Wind load analysis was performed considering a basic wind speed of 39 m/s corresponding to the selected geographical location. Wind loads were applied in both X and Z directions to evaluate the critical structural response. Wind analysis was carried out according to IS 875 (Part 3): 2015 provisions.

g) Seismic Load

Seismic analysis was performed according to the provisions of IS 1893 Earthquake Resistant Design Code Overview. The stadium roof structures were assumed to be located in Seismic Zone III.

h) Time History Loading

The El-Centro earthquake acceleration record was used as input ground motion data for linear time history analysis. The seismic excitation was applied at the supports of the structure to evaluate the post-dynamic response characteristics of the roof systems.

3.5 Dynamic Analysis

Dynamic analysis was carried out to study the behavior of the stadium roof structures under seismic excitation and to determine the influence of roof geometry on structural response.

Two types of dynamic analyses were performed:

1. Response Spectrum Analysis (RSA)
2. Linear Time History Analysis

i) Response Spectrum Analysis

Response Spectrum Analysis was conducted to determine modal properties such as natural frequency, mode shapes, and time period of the structures. The method estimates the peak structural response under seismic loading by combining modal responses statistically.

The response spectrum was defined according to IS 1893:2002 for 5% damping.

j) Time History Analysis

Linear Time History Analysis was performed using El-Centro earthquake acceleration data to obtain the variation of structural response with time. This method provides detailed information regarding displacement, internal force, and vibration characteristics throughout the duration of ground motion.

The following structural parameters were evaluated during the analysis:

- Maximum displacement
- Maximum section force
- Natural time period
- Frequency
- Maximum shear force
- Modal behavior
- Dynamic response characteristics

The results obtained from the analysis were compared to determine the most structurally efficient and dynamically stable stadium roof configuration.

III. RESULT AND DISCUSSION

Wind load analysis was carried out considering a basic wind speed of 39 m/s with 50% exposure. Loads were applied in both X and Z directions to evaluate structural response. The results show that the flat roof experiences higher displacement, while the inclined roof performs moderately better. The curved roof shows the best performance due to reduced wind pressure and improved aerodynamic behavior. Wind in the Z-direction is more critical compared to the X-direction.

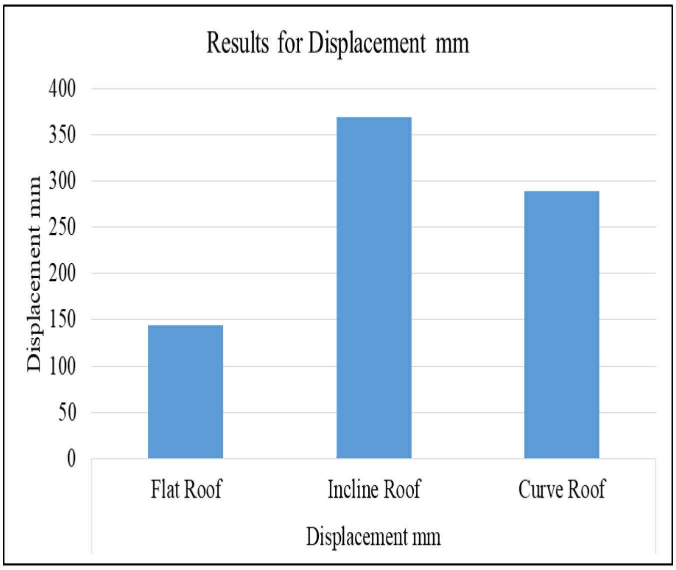
The load combination 1.5 (DL + WL) was considered to evaluate the maximum structural response under combined dead and wind loads. This combination represents the ultimate limit state condition as per design standards.

A. Results for Wind Load Analysis

Result For Displacement

Table 1 Results for Displacement mm

Displacement mm		
Flat Roof	**Incline Roof**	**Curve Roof**
143.56	368.96	288.7



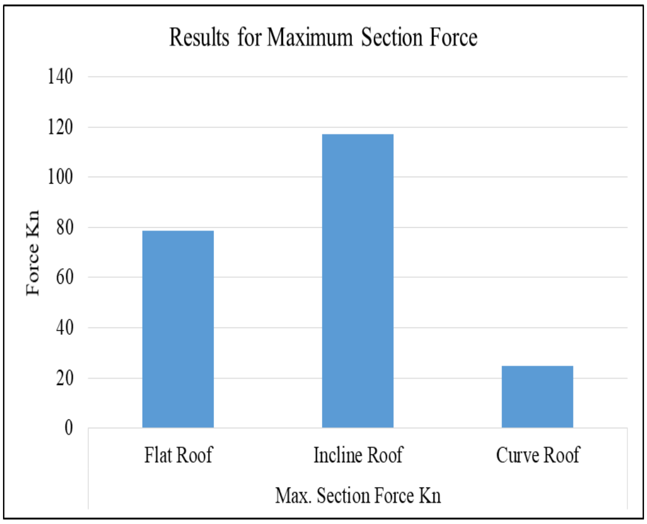
Graph 1 Results for Displacement mm

The inclined roof shows the highest displacement (368.96 mm), which is about 157% higher than the flat roof, indicating poor stiffness. The curved roof has a displacement of 288.7 mm, approximately 101% higher than the flat roof, but about 21.8% lower than the inclined roof. The flat roof shows the least displacement (143.56 mm), demonstrating maximum stiffness and minimum deformation.

Results for Maximum Section Force Kn

Table 2 Result for Max. Section Force Kn

Max. Section Force Kn		
Flat Roof	**Incline Roof**	**Curve Roof**
78.79	117.27	24.86



Graph 2 Result for Max. Section Force Kn

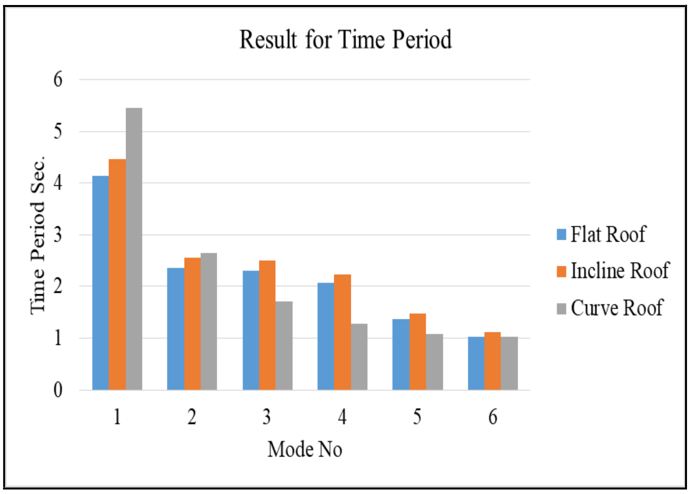
Table 4.2 presents the maximum section forces for different stadium roof models. The inclined roof shows the highest force (117.27 kN), which is about 48.8% higher than the flat roof, indicating higher stress in members. The flat roof has a force of 78.79 kN, while the curved roof shows the least force (24.86 kN), which is approximately 68.5% lower than the flat roof and 78.8% lower than the inclined roof.

B. Result For Response Spectrum Analysis

Result for Time Period and Frequency

Table 3 Result for Time Period Sec

Time Period Sec.			
Mode	**Flat Roof**	**Incline Roof**	**Curve Roof**
1	4.134	4.46	5.457
2	2.348	2.55	2.641
3	2.31	2.508	1.714
4	2.065	2.228	1.282
5	1.374	1.484	1.08
6	1.03	1.113	1.03
Average	**2.210**	**2.391**	**2.201**



Graph 3 Result for Time Period Sec

The response spectrum analysis shows that the roof geometry has a significant effect on the natural time period of the stadium structure. In Mode 1, the curve roof recorded the highest time period of 5.457 sec, which is 31.96% higher than the flat roof and 22.35% higher than the incline roof, indicating greater flexibility. The incline roof also showed a 7.88% increase compared to the flat roof.

IV. CONCLUSION

This study presented a comparative analysis of stadium roof structures with flat, inclined, and curved geometrical configurations subjected to wind and dynamic loading conditions using STAAD.Pro. The structural performance of each roof form was evaluated based on displacement, section force, natural time period, frequency, and shear force responses.

The results of wind load analysis showed that roof geometry has a significant influence on structural behavior. The flat roof exhibited the minimum displacement, whereas the inclined roof showed the maximum displacement under wind loading. However, the curved roof demonstrated better overall structural efficiency by developing the least section force among all roof configurations, indicating improved load distribution and reduced stress concentration due to its aerodynamic shape.

The response spectrum analysis revealed that the curved roof possessed the highest fundamental time period, indicating greater flexibility and better capability to absorb dynamic effects. Frequency analysis further showed that the curved roof had lower frequency in the initial mode and comparatively higher frequencies in higher modes, reflecting improved stiffness characteristics and stable dynamic performance.

The shear force results also confirmed the effectiveness of the curved roof configuration, as it recorded the minimum shear force compared to flat and inclined roofs. This indicates better resistance to lateral forces and improved overall structural stability.

Based on the comparative evaluation, the curved roof configuration demonstrated superior overall performance under both wind and dynamic loading conditions. Its aerodynamic form, lower internal force generation, improved dynamic response, and enhanced lateral stability make it a more efficient and suitable option for long-span stadium roof structures.

REFERENCES

1. Ahiwale, D., Shaha, P., Palaniyandi, K. et al. “Quantification study for roof truss subjected to near-fault ground motions.” Innovative Infrastructure Solutions, Vol. 6, Article 118, 2021. DOI: 10.1007/s41062-021-00478-0
2. Tüfekci, M., Tüfekci, E., & Dikicioğlu, A. “Numerical Investigation of the Collapse of a Steel Truss Roof and a Probable Reason of Failure.” Applied Sciences, Vol. 10, No. 21, 2020. DOI: 10.3390/app10217769
3. Tahmasebinia, F., Chen, E., Huang, A., & Li, J. “Designing Lightweight Stadium Roofing Structures Based on Advanced Analysis Methods.” Sustainability, Vol. 15, No. 4, Article 3612, 2023. DOI: 10.3390/su15043612
4. Muslikh & Iman, Miftahul. “Cold-Formed Steel Truss Roof Structure Failure Considering Seismic Load and Buckling Analysis.” Journal of the Civil Engineering Forum, Vol. 12, No. 1, 2025. DOI: 10.22146/jcef.13069
5. Zhang, C., Li, J., Liu, Y., Cheng, Q., Sun, Z. “Seismic Vulnerability Analysis of Concrete-Filled Steel Tube Structure under Main–Aftershock Earthquake Sequences.” Buildings, 2024. DOI: 10.3390/buildings14040869
6. Sunil Kumar Yadav & Rahul Kumar Satbhaiya “Analysis of a Stadium Structure under Dynamic Loading Using Analysis Tool a Review.” International Journal of Scientific Research in Civil Engineering, 2025.
7. Masoud Babaei, Kamran Asemi et al. “Applying Improved Performance-Based Instructions to Investigate Seismic Performance of a Code-Conforming Steel Trussed-Tube Building.” Buildings, 2025. DOI: 10.3390/buildings15010034
8. Joseph, J. R., Henderson, J. H. “Concrete-filled steel tube truss girders a state-of-the-art review.” Journal of Engineering and Applied Science, 2023. DOI: 10.1186/s44147-023-00220-w
9. Labò, S., Marini, A., Giuriani, E. P., Zanni, J., Riva, P. “Seismic Risk Mitigation of a Long-Span Historical Building Through a Wooden Roof-Box Structure.” In Structural Analysis of Historical Constructions. SAHC 2023, RILEM Bookseries, vol. 47, Springer, Cham, 2024. DOI: 10.1007/978-3-031-39603-8_86.MDPI Sustainability (2020).