

A Review on Comparative Dynamic Analysis of Stadium Roof Structures With Varying Geometrical Forms

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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 specially engineered roofing system designed to cover large open spaces while providing protection from environmental conditions such as sunlight, rain, wind, and extreme temperatures. In modern infrastructure, stadium roofs are not only functional elements but also important architectural features that contribute to the aesthetic appearance and identity of sports arenas and public gathering facilities. Unlike conventional building roofs, stadium roofs are required to span very large distances without intermediate supports in order to provide unobstructed visibility for spectators and maximum utilization of internal space.

In recent decades, the development of retractable and long-span roof systems has gained significant attention due to rapid advancements in structural engineering, construction technology, and architectural innovation. A retractable stadium roof is a movable roof system that can slide or roll back on tracks, allowing the interior of the structure to be either completely enclosed or open to the outdoor environment as required. Such systems are operated mechanically through motors and automated control systems. Retractable roofs are also referred to as operable roofs, while systems that open through hinge mechanisms are generally called operable skylights. These roof systems are widely used in sports

stadiums, swimming complexes, auditoriums, restaurants, public gathering spaces, and residential buildings to create flexible indoor-outdoor environments.

Modern stadiums are considered landmarks of engineering excellence because they combine structural efficiency, functionality, and architectural creativity. The roof system is one of the most critical structural components of a stadium because it directly influences the safety, serviceability, durability, and comfort of the facility. Stadium roofs are typically lightweight structures with complex geometrical configurations such as domes, arches, cable-supported systems, space frames, shell roofs, and tubular truss systems. Due to their lightweight nature and large unsupported spans, these roofs are highly sensitive to external dynamic forces, especially wind and earthquake loads.

Dynamic loading produces vibrations and structural responses that may significantly affect the stability and performance of the roof system. Earthquake-induced ground motions generate inertial forces throughout the structure, leading to displacement, stress concentration, and vibration. Therefore, dynamic analysis becomes essential for evaluating the seismic behaviour of stadium roof structures. The geometry of the roof plays a major role in determining its structural characteristics, including stiffness, natural frequency, damping behaviour, load transfer mechanism, and overall stability. Even small changes in roof shape or structural arrangement can produce considerable variations in seismic response.

Among various structural systems used for stadium roofs, tubular truss systems are widely preferred because of their high strength-to-weight ratio, ease of fabrication, architectural flexibility, and efficient load distribution capability. Tubular trusses can effectively resist axial forces while reducing the self-weight of the structure, making them highly suitable for long-span applications. Different roof configurations such as curved roofs, barrel vault roofs, dome roofs, arch-supported roofs, and space frame roofs exhibit different seismic performances under earthquake excitation. Therefore, comparative study and analysis of different stadium roof geometries are necessary to identify structurally efficient, economical, and safer roof systems.

The increasing demand for multi-purpose sports facilities and entertainment complexes has further increased the need for innovative roof systems capable of withstanding severe environmental conditions while maintaining architectural appeal. Engineers and researchers continuously focus on improving roof performance through advanced materials, computational analysis, and optimized structural configurations. Modern structural analysis software such as ETABS, SAP2000, STAAD Pro, and ANSYS enables engineers to study complex dynamic behaviour and accurately predict the response of stadium roof systems under seismic loading conditions.

The present study focuses on the dynamic analysis of different stadium roof structures under earthquake loading. The objective is to understand how variations in roof geometry influence seismic response parameters such as displacement, base shear, natural time period, mode shape, and stress distribution. The study aims to compare the structural behaviour of various roof forms and identify the most effective configuration for achieving better seismic performance and structural safety.

1) A. History

The concept of movable and retractable roof systems originated during the mid-twentieth century as engineers sought to develop structures capable of providing both indoor protection and open-air experience. According to records from the United States Patent and Trademark Office (USPTO), David S. Miller, founder of Rollamatic Roofs, filed a patent in August 1963 for a movable and remotely controllable roof section intended for houses and other buildings. Since Rollamatic had already been established nearly five years earlier, the first installation of a motorized retractable roof is believed to have been completed sometime between 1958 and 1963.

Over time, retractable roof technology evolved significantly with improvements in materials, automation systems, and structural engineering techniques. Initially used in small residential and commercial buildings, retractable roof systems gradually became popular in large sports stadiums and

entertainment arenas around the world. Today, advanced stadium roof systems integrate modern technologies such as automated control mechanisms, lightweight steel structures, tensile membranes, and energy-efficient materials to achieve improved structural performance, operational flexibility, and spectator comfort.

II. STATE OF DEVELOPMENT

Ahiwale, D., Shaha, P., Palaniyandi, K. et al. (2021)

The effects of vertical seismic excitations have a considerable destructive potential for long-span structures, particularly for near-field earthquakes. A quantification analysis is carried out in this paper to describe the response of a 25-m long trapezoidal truss frame with a height of 9 m under Vertical Ground Motion (VGM) with the help of eight near-field seismic excitations. Linear analysis of earthquake load combinations, including VGMs, has been conducted. The VGMs are leading the design of the long-span roof truss rather than the wind load. The time history analysis is therefore performed for horizontal ground acceleration and horizontal plus vertical acceleration using SAP 2000.

Tüfekci, M., Tüfekci, E., & Dikicioğlu, A. et. al. (2020)

This study investigated the failure of the roof, with steel truss construction, of a factory building in Tekirdag in the north western part of Turkey. The investigation includes detailed numerical modelling of the truss roof system, identification of weak links in the structure and examination of possible failure modes under loads. It is found that design deficiencies, material non-uniformity, incorrect assumptions in load paths, and local buckling are probable reasons for collapse. The results suggest that better design practice, especially considering realistic loadings, stability issues and proper connection detailing, is essential for safety.

Tahmasebinia, F., Chen, E., et. al. (2023)

The current structural engineering practical standards are unable to offer an universal structural design standard for long-spanning lightweight stadium roofing structures. Linear static analysis will then be undertaken where critical members will be identified within the model. Based on this, preliminary member sizing and design feasibility checks will be conducted in order to ensure structural stability and compliance to the Australian Steel Structure code AS4100:2020. A linear buckling analysis is also conducted based on the selected sizes from the initial stage to determine critical loads. Advanced analysis including non-linear buckling computation is comprehensively managed. Some of the crucial parameters such as maximum displacement, maximum/minimum principal stresses, critical buckling loads, as well as load factors are examined. The main novelty of this study is to

determine a clear road map to design stadium roofing systems subjected to a combination of different types of the loading.

Muslikh & Iman, et. al. (2025) There were many incidents of cold-formed steel roof truss structures in the last 5 years in Indonesia. Various kinds of allegations have been addressed to cold-formed steel material applications especially in the case of seismic resistance. Some of them concern the authenticity of the steel material itself and the selection of cold formed steel material. On the other hand, recently, people have installed (assembled) cold-formed steel trusses without involving a certified cold-formed steel applicator. The study aims to examine such failures, perform seismic load and buckling analyses on cold-formed steel truss roofs, and identify critical failure modes. The paper concludes that improper material selection, inadequate member design, and lack of consideration for buckling under seismic effects are key vulnerabilities.

Zhang, C., Li, J., Liu, Y., Cheng, et. al. (2024) Earthquakes are often followed by higher-intensity aftershocks, which tend to aggravate the accumulated and more severe damage to building structures. The seismic vulnerability of concrete-filled steel tube (CFST) structures under major aftershocks is more complex. In this paper, a CFST frame and a frame with buckling-restrained braces (BRBs) are studied, and the finite element analysis software Midas 2022 is used to analyze the seismic vulnerability of the two types of structures under main shock and main-aftershock. The results show that the structural vulnerability of the two structures is significantly higher under the main-aftershock sequences than under the main shock alone. Compared with the CFST structure, the structure with BRBs can effectively reduce the structural displacement and the hysteretic energy, decrease the plastic deformation risk of the structural components, and improve the seismic performance. The structure with BRBs can significantly reduce the probability of structural collapse under the main-aftershock sequence and can provide a reliable guarantee of the stability of the building.

Sunil Kumar Yadav et. al. (2025)

This study provides a comprehensive analysis of the design of a multifunctional stadium constructed of reinforced concrete (RCC) using STAAD.Pro software. The primary focus is on how the structure behaves under various stresses, including seismic, wind, dead, and live loads. The stadium's geometry and material properties were modelled using STAAD. The primary focus is on wind and seismic loads and how they impact the structural behavior of the stadium. STAAD.Pro was used to model a 21-meter stadium structure, including all of the material properties, boundary conditions, and intricate geometry.

Masoud Babaei, Kamran Asemi et al. (2025) Despite the many advantages of tube systems with braces, known as trussed tubes, no specific seismic design criteria exist in the current regulations to design them, and practitioners utilize common methods used for common building structures to deal with designing such systems. In the current study, the seismic performance of a code-conforming tall building with a trussed-tube system has been investigated using the performance-based instructions of the ASCE 41 standard. The structure has primarily been designed using code-based response spectrum analysis. Moreover, the adequacy of the final design has then been rechecked through the application of a linear time-history analysis with an ensemble of seven pairs of spectrally matched earthquake records. To assess the performance of the designed structure, a three-dimensional nonlinear static analysis has been employed at two different hazard levels to examine whether the steel structural components, including the braces, columns, and beams, meet the acceptance criteria at the specified performance objective. Based on the obtained results, it has been observed that the code-conforming structure does not satisfy the performance objectives at either of the two hazard levels. Single braces, as well as columns at lower stories, have been found to be the most critical elements requiring reconsideration in their design.

Joseph J. R., et. al. (2023)

This paper reviews the existing literature and applications of concrete-filled steel tube truss girders. Key aspects covered include design approaches, structural behaviour under load, fatigue, buckling, and composite action between concrete infill and steel tube. The review synthesizes findings from experimental, analytical, and numerical studies, highlighting gaps such as behavior under dynamic loads and seismic performance of such girders in long-span roof and truss structures.

Labò S., Marini A., Giuriani E. P., et. al. (2024) This paper presents a case study dealing with the seismic risk mitigation of a long-span historical building, focusing on the roof-box structure composed of wooden elements. The study involves retrofitting strategies to improve seismic performance while preserving architectural and historical features. Through numerical modelling and historical structural analysis, the roof box's behavior under earthquake loads is evaluated, and interventions are proposed aiming to reduce damage during seismic events, considering both structural safety and heritage conservation.

III. CONCLUSION

The present review study concludes that stadium roof structures are among the most complex and dynamically sensitive structural systems used in modern civil engineering. Due to their large span dimensions, lightweight characteristics, and architecturally advanced geometrical forms, these structures are highly influenced by dynamic loading conditions such as earthquakes and wind forces. The literature reviewed in this study clearly establishes that the seismic behaviour of stadium roof systems depends greatly on factors such as roof geometry, structural configuration, stiffness distribution, member slenderness, support conditions, and material properties.

The review highlights that tubular truss systems are widely preferred in stadium roof construction because of their high strength-to-weight ratio, efficient load transfer mechanism, reduced self-weight, and architectural flexibility. Tubular members effectively resist axial forces while allowing the construction of large column-free spaces required in stadium structures. However, despite their structural advantages, tubular roof systems remain vulnerable to dynamic effects such as excessive vibration, instability, local buckling, and stress concentration under severe seismic excitations. Therefore, detailed dynamic evaluation becomes essential for ensuring structural safety and long-term performance.

From the reviewed studies, it is observed that roof geometry has a major influence on the dynamic response of stadium structures. Different geometrical forms such as dome roofs, radial trusses, barrel vaults, curved roofs, and asymmetric roof systems exhibit different stiffness characteristics, natural frequencies, and load distribution patterns. Symmetrical roof configurations generally provide better structural balance and uniform load transfer, whereas irregular and asymmetric geometries may lead to torsional effects, uneven stress distribution, and increased displacement during seismic events. Hence, the selection of an appropriate roof geometry plays a vital role in improving the seismic performance and structural efficiency of stadium roofs.

The literature also demonstrates the importance of advanced seismic analysis techniques in evaluating realistic structural behaviour. Conventional static analysis methods are often insufficient for long-span roof structures because they cannot accurately capture dynamic effects produced by earthquake ground motions. As a result, advanced analytical procedures such as nonlinear time-history analysis, response spectrum analysis, and performance-based seismic analysis are increasingly adopted by researchers and engineers. These methods help in understanding displacement response, internal member forces, vibration characteristics, energy dissipation behaviour, and failure mechanisms under actual earthquake conditions.

Another important observation from previous studies is that vertical ground motion significantly affects long-span stadium roof systems. Many traditional structural designs mainly consider horizontal seismic forces, while vertical seismic effects are often neglected. However, research findings indicate that vertical earthquake excitations can generate substantial additional stresses and may even govern the design of lightweight roof trusses. Therefore, both horizontal and vertical seismic components should be considered during the analysis and design of stadium roof structures for accurate prediction of structural response.

The reviewed literature further indicates that inadequate connection detailing, improper member sizing, unrealistic load assumptions, and insufficient consideration of buckling effects are among the major causes of roof failures in steel truss systems. Several studies emphasize that local buckling and instability of slender tubular members can lead to progressive structural failure during seismic events. Consequently, proper compliance with design standards, accurate modelling techniques, and careful detailing of structural connections are necessary to improve the reliability and safety of stadium roof systems.

Modern computational tools such as STAAD.Pro, SAP2000, MIDAS, ETABS, and ANSYS have become highly effective for analysing complex stadium roof structures. These software platforms enable engineers to model intricate geometries, apply realistic loading conditions, and study dynamic responses with greater accuracy. However, several studies also recommend validating numerical results using simplified analytical methods or experimental investigations to ensure the reliability of computational analysis.

Based on the overall review, it can be concluded that dynamic analysis is essential for the safe and economical design of modern stadium roof structures. The comparative evaluation of different geometrical forms helps in identifying roof configurations that offer improved seismic resistance, reduced displacement, better energy dissipation, and enhanced structural stability. The study also identifies the need for further research on post-dynamic behaviour, residual deformation, multiple earthquake ground motion analysis, and design approaches based on Indian standards such as IS 801:2005. Future investigations in these areas will contribute significantly toward the development of safer, more efficient, and structurally optimized stadium roof systems capable of performing effectively under severe seismic conditions.

IV. Gap Identification

- Design of stadium roof as tubular structure: While tubular truss systems are widely used for long-span

roofs, few studies have focused on designing stadium roofs specifically according to Indian standard IS 801:2005, considering member sizing, connections, and overall geometry.

- Dynamic analysis under multiple ground motions: Many studies analyze seismic response under a single or simplified ground motion. There is a lack of comprehensive dynamic analysis of different stadium roof geometries subjected to multiple recorded earthquake ground motions using time-history methods.
- Post-dynamic behavior assessment: Most research focuses on immediate seismic response (displacement, internal forces) but does not sufficiently explore the post-dynamic performance, such as residual stresses, deformation patterns, and structural stability after seismic excitation.

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