A state of arts on Seismic Performance Evaluation of Reinforced Roof Shell Structures

Vijay Kumar Shukla[1], Dr. Ram Narayan Khare[2]

1. *Ph.D research Scholar, Vishwavidyalaya Engineering College, Ambikapur*
2. *Principal, Vishwavidyalaya Engineering College, Ambikapur*

Abstract:

Reinforced roof shell structures have gained prominence in seismic regions due to their potential to mitigate seismic effects through their unique architectural and structural characteristics. This paper presents a critical review of the seismic performance of reinforced roof shell structures, focusing on their design principles, structural behaviour under seismic loading, and effectiveness in enhancing structural resilience. The review synthesizes current research findings, methodologies, and case studies to evaluate the performance metrics such as seismic resistance, deformation characteristics, and damage assessment criteria. Key factors influencing the seismic performance, including material properties, construction techniques, and retrofitting strategies, are analysed to provide insights into improving the seismic resilience of these structures. Furthermore, challenges and opportunities for future research and development in this field are discussed, aiming to guide future advancements in the design and construction practices of reinforced roof shell structures in seismic environments.

Keywords: reinforced roof shell structures, seismic performance, seismic loading, structural resilience

Introduction

Reinforced roof shell structures have emerged as a compelling architectural and engineering solution, particularly in seismic regions where the ability to withstand earthquakes is paramount. Characterized by their curved, shell-like forms, these structures offer both aesthetic appeal and structural efficiency by minimizing material use while spanning large areas without internal supports. The inherent geometric properties of roof shell structures contribute significantly to their seismic performance, as they distribute forces dynamically and effectively across their surfaces. In recent decades, advancements in computational modelling, material sciences, and seismic engineering have enhanced our understanding of how these structures behave under seismic loading. Design principles have evolved to optimize seismic resilience, taking into account factors such as geometry, material properties, and construction techniques. The implementation of performance-based design criteria and adherence to stringent seismic codes have further bolstered the safety and durability of roof shell structures in earthquake-prone regions.

Despite these advancements, challenges remain in accurately predicting and mitigating the effects of seismic forces on roof shell structures. Factors such as complex dynamic interactions, ground motion characteristics, and the variability of seismic events pose ongoing challenges to engineers and architects striving to improve structural performance and safety.

This critical review aims to consolidate current knowledge and research findings on the seismic performance evaluation of reinforced roof shell structures. By synthesizing existing literature, case studies, and theoretical analyses, this paper will explore the structural behaviour, design principles, effectiveness in enhancing resilience, influencing factors, challenges, and future opportunities for these unique architectural forms in seismic environments.

Through this comprehensive examination, we seek to provide valuable insights into the state-of-the-art practices, identify gaps in current understanding, and propose directions for future research and development in the field of seismic design for roof shell structures. Ultimately, this review aims to contribute to the ongoing efforts to advance seismic engineering practices and enhance the safety and sustainability of built environments in earthquake-prone regions.

Literature Review

1. ***Literature Survey on Reinforced Concrete Shell Structures-***

a. Historical Development of Reinforced Concrete Shell Structure

A) The historical development of reinforced concrete shell structures is a fascinating journey through innovation and engineering advancements.

A1. Early Foundations (Late 19th to Early 20th Century)

a. Proto-Reinforced Concrete Shells:

- **Joseph Monier (1860s):** Joseph Monier, a French gardener, was one of the earliest pioneers in the use of reinforced concrete. He experimented with concrete pots and planters that used a mesh of iron bars. Although not shell structures per se, Monier's work laid the groundwork for future developments in reinforced concrete.

b. Early 20th Century Innovations:

- **Architects and Engineers:** During this period, architects and engineers began exploring the potential of reinforced concrete. Architects like Auguste Perret and engineers like François Hennebique experimented with new construction techniques.

A2. Emergence of Reinforced Concrete Shells (1920s-1940s)

a. The Birth of Reinforced Concrete Shell Design:

- **Antonio Gaudí (1920s):** Gaudí's work on the Sagrada Familia in Barcelona was significant in the development of shell structures, though his methods were more intuitive than theoretical.

b. Theoretical Foundations:

- **Gustav Eiffel and Robert Maillart:** Eiffel's iron structures and Maillart's concrete bridges pushed the boundaries of structural engineering. Maillart, in particular, designed the famous Salginatobel Bridge, demonstrating the potential of concrete structures.

A3. Development of Modern Reinforced Concrete Shell Structures (1950s-1970s)

a. Advanced Theoretical and Practical Techniques:

- **Pier Luigi Nervi (1950s-60s):** Nervi was a key figure in the development of reinforced concrete shell structures. His work combined artistic vision with engineering innovation, designing iconic structures such as the Palazzetto dello Sport in Rome.

b. Structural Analysis and Design Innovations:

- **A. G. M. Michell (1940s):** Michell's work on the minimal surface theory and the concept of optimal structures influenced the design of efficient shell structures.

c. Development of Concrete Shells:

- **Design of Large-Scale Structures:** This era saw the creation of large, complex shell structures like the Sydney Opera House (1973) by Jørn Utzon, which used precast concrete shells for its iconic roof.

A4. Modern Era and Technological Advancements (1980s-Present)

a. Computer-Aided Design and Analysis:

- **Finite Element Analysis:** The introduction of computer technology and finite element analysis revolutionized the design of shell structures, allowing for more complex and efficient designs.

b. Sustainable and Innovative Designs:

- **Recent Developments:** Contemporary architects and engineers are focusing on sustainable materials and construction methods. Innovations include the use of advanced computational design techniques, environmentally friendly materials, and energy-efficient design practices.

c. Iconic Modern Shell Structures:

- **Contemporary Examples:** Structures such as the Eden Project (2001) by Sir Norman Foster and the National Stadium in Beijing (2008) showcase modern advancements in reinforced concrete shell design.

Conclusion is that the development of reinforced concrete shell structures reflects broader trends in engineering and architecture, from early experimental uses of concrete to the sophisticated, high-tech designs of today. The evolution of this field demonstrates a blend of artistic vision and engineering innovation that continues to shape modern architecture.

b. Survey on research work done for Reinforced Concrete Shell Structure

[1]D. Veenendaal, J. Bakker & P Block (2017) has describes the geometry and structural design of a flexibly formed, mesh-reinforced sandwich shellroof, as part of the NEST HiLo project, to be built in Dübendorf, Switzerland, in 2016. The computational designprocess consists of an integrated parametric model used for multi-objective evolutionary shape optimization ofthe shell, and subsequent analysis of its nonlinear behaviour.

[2]G.Nie et.al (2014) has worked on a single-layer reticulated dome under seismic load, parametric analyses through increment dynamic analysis (IDA) are conducted on the dome to under failure mechanism. The results of the analyses indicate that the limit load of the structure significantly increases together with the plastic development with the decreasing rise-span ratio, roof mass and initial defects prior to the failure to collapse. Then, the fragility curves of the different values of the structural damage model with the corresponding different degrees of damage under seismic records are obtained through IDA analysis which can be used for seismic performance evaluation and risk assessment for its loss or fatality acceptability.

[3]***T.Tysmans et.al (2009)*** used a parametric study to evaluate the structural applicability of TRC for small span (2-15 m) doubly curved roof shells. The application of two different, existing TRC material combinations demonstrates the influence of the applied composite material on the design of the shell.

[4]***S. Chandrasekaran et.al (2009)*** presents design curves for reinforced concrete open barrel cylindrical shells for different geometric parameters in his study. The analysis is done in two parts namely: i) RC shell subjected to uniformly distributed load that remain constant along its length and curvature of the shell surface; and ii) RC shell subjected to uniformly distributed load varying sinusoidally along its length in addition to different symmetric edge loads present along its longitudinal boundaries. Design charts are proposed for easier solution of shell constants after due verification of results obtained from finite element analysis.

[5]***A. E. Assan (2002)*** has done analysis of reinforced concrete cylindrical shells is performed using a strain-based finite element. The shell element employed is bi-dimensional, cylindrical circular and has four-nodes and five nodal degrees of freedom. The nonlinearities due to concrete cracking and yielding of the steel are taken into account. The constitutive models for the materials employ the smeared cracking concept and a finite element layered approach. Concrete is modelled by a strain-induced orthotropic-elastic model under plane state of stress. A bilinear steel model is used and the stress/reversal with Bauschinger effect is included. Examples show the good accuracy provided by this analysis.

[6]***J. Berger et.al (2020)*** was present a novel approach for shell-construction that circumvents the necessity for doubly curved formwork. Instead, shells are erected from flat plates to which an eccentric force is applied causing them to bend into a desired curved shape. The form-activating forces are induced by coupling a system of tendons to a thin—thus flexible—plate made from reinforced concrete. This approach may seem controversial as concrete exhibits a small ultimate strain and a brittle failure behaviour. Therefore, it does not appear suited for the large deformations expected during the construction of actively bent structures. The investigations presented in this paper show the suitability of textile-reinforced concrete for the fabrication of actively bent shells.

[7]***V. Sravana & Jyothi PG (2015)*** presented the analysis and design of shell structures of circular cylinder shape have been done using D.K-J theory and Schorer theory D-K-J Theory has been used for design of short shell with edge beam and Schorer theory has been used for the analysis of long shell with edge beam. Reinforcement details have been provided based on calculations of stress resultants at different sections of the shell.

[8]***I. Karhut et.al (2021)*** has presented mathematical modelling and experimental studies for the stress-strain state of the annular section of the reinforced concrete shell with the protective structure are presented. Computer simulation has been formulated as a stationary temperature problem. The distribution of deformations and stresses is shown using the equations of the elastic theory. A comparison of theoretical dependences on the results of experimental studies of physical models is given. Conclusions are drawn about the possibility of using them in the calculations of reinforced concrete protective structures.

2. Survey on Pushover Analysis, Time History Analysis and Fragility Curve

[9]**M. Khorami et.al (2017)** has presented the seismic behavior of BRBF structures is studied and compared with special concentric braced frames (SCBF). To this purpose, three BRBF and three SCBF structures with 3, 5 and 10 stories are designed based on AISC360-5 and modelled using OpenSees. These structures are loaded in accordance with ASCE/SEI 7-10. Incremental nonlinear dynamic analysis (IDA)

are performed on these structures for 28 different accelerograms and the median IDA curves are used to compare seismic capacity of these two systems. Results obtained, indicates that BRBF systems provide higher capacity for the target performance level in comparison with SCBF systems. And structures with high altitude (in his study, 5 and 10 stories) with the possibility of exceeding the collapse prevention performance level, further than lower altitude (here 3 floors) structures.

[10]**G.Nie et.al (2017)** is used a ductile damage constitutive model to describe the damage evolution of material while a structure is subjected to earthquake loading. And embedding this constitutive model into UMAT subroutine using software ABAQUS to introduce damage constitutive equations. The collapse mechanism of single-layer reticulated shell was investigated through incremental dynamic analysis (IDA). The vulnerability at different damage degrees of structure using the structural damage model was conducted through IDA analysis, which could be used for seismic performance evaluation and risk assessment.

[11]**M. Manjuprasad et.al (2001)** has presented the details of a non-linear dynamic analysis carried out at SERC, Madras on a reinforced concrete (RC) secondary containment shell subjected to seismic load, taking into account the non-linearities of reinforced concrete in the finite element modelling. In his worked A 20-noded, three-dimensional, solid isoparametric finite element is used for spatial discretisation. By using elasto-viscoplastic property for concrete in compression and representing reinforcement with smeared approach. The influence of these two parameters on the non-linear response and ultimate behaviour of the structure give the performance of structure against non-linearities.

[12]**H. Kabtamu et. al (2018)** has compared the dynamic analysis of Soil-Structure Interaction (SSI) effects on 7 and 12-story RC frames on soft soil (flexible base) and fixed base. Two methods, Winkler Spring and half-space direct, are used for soft soils with $V_s < 150 \, \text{m/s}$, per Chinese GB50011-2010 and Ethiopian ES8-2015 codes. Frames are subjected to ground motions matched to these codes for linear time history analysis. 90% mass participation: 2-3 modes (Spring/Fixed), 11-30 modes (Direct), Flexible bases: Longer vibration periods, larger inter-story drift, smaller base shear, Spring model: Larger drift and P-Δ at lower stories, Direct method: Larger drift and P-Δ at upper stories. Finally he concluded with that base shear reduction due to SSI is not always beneficial due to increased P-Δ effects at lower stories.

[13]**Y. Menasri and M. Brahimi (2024)** has presented presents a probabilistic approach using seismic fragility curves to assess SSI effects on mid-rise (four-story) RC frames. Two models are analyzed: fixed base and with SSI, using an elastic soil model. Static Pushover to Incremental Dynamic Analysis (SPO2IDA) evaluates the RC frame response.Ultimate displacement ratios for rigid base vs. SSI for soils S1 (rock), S2 (stiff), S3 (soft), and S4 (very soft) are 4%, 19%, 25%, and 46%, respectively. Results show that not accounting for SSI in designs of short-period structures on soft soils (S3, S4) increases vulnerability and damage probability during large earthquakes.

[14]**G. B. Nie et. al (2014)** has parametrically analysed via Incremental Dynamic Analysis (IDA) conducted on a single-layer reticulated dome to understand its seismic failure mechanism by Limit load increases with decreasing rise-span ratio, roof mass, and initial defects due to that Plastic development decreases, and ductility worsens with smaller cross-section areas, Failure occured due to dynamic strength failure from excessive material damage and a structural damage model estimates in varying damage degrees finally fragility curves for different damage degrees are obtained via IDA for seismic performance evaluation and risk assessment.

Conclusions

By the survey of various paper based on proposed title concludes that significant progress has been made in understanding and predicting the seismic behaviour of these structures. Advanced analytical and numerical methods, particularly nonlinear static and dynamic analyses, are essential for accurate performance evaluations. The impact of soil-structure interaction (SSI) is critical, especially for structures on soft soils, and must be considered to avoid underestimating vulnerability. Developing fragility curves is vital for risk assessment and performance-based design. Despite these advancements, there remains a need for more experimental validation and innovative design approaches to enhance seismic resilience. Future research should address multi-hazard scenarios and improve computational tools to ensure the safety and reliability of reinforced roof shell structures under seismic loads.

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