Seismic Response and Fragility Assessment of Reinforced Concrete Shell Structures: A Methodological Framework

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Abstract

Reinforced concrete (RC) shell structures are increasingly used in modern construction due to their architectural appeal and efficient structural performance. However, their seismic behavior remains less understood compared to conventional framed structures. This paper presents a comprehensive methodology for modeling and seismic analysis of RC shell structures under earthquake loading. The proposed framework integrates nonlinear static pushover analysis, the N2 method for transforming multi-degree-of-freedom systems into equivalent single-degree-of-freedom models, nonlinear dynamic time-history analysis, incremental dynamic analysis (IDA), and fragility assessment. Finite element modeling using SAP2000 with layered shell elements is adopted to capture realistic structural behavior. The methodology is demonstrated for a representative RC shell, providing insights into its capacity, demand, and performance under seismic actions. The study highlights the applicability of advanced nonlinear methods for performance-based seismic design of RC shell structures and identifies future research directions.

Keywords

Reinforced Concrete Shell Structures; Seismic Analysis; Pushover; N2 Method; Fragility Curves; SAP2000

1. Introduction

Reinforced concrete (RC) shell structures, characterized by their curved geometries and large span coverage, have been adopted in architectural and engineering practice for their efficiency in carrying loads through membrane action. Their potential for seismic resilience stems from their inherent stiffness and geometric form. However, compared to framed structures, research and guidelines for seismic performance of shell structures remain limited. Design codes, including Indian Standards (IS), lack specific provisions for shell structures under seismic loads, necessitating, systematic research.

The motivation of this study arises from the inadequacy of established procedures for analyzing RC shells under earthquakes. While nonlinear static pushover analysis and performance-based seismic design have become standard for buildings, their adaptation to long-span and shell-type structures is still under development. The present research aims to bridge this gap by proposing a unified methodology for seismic performance evaluation of RC shells.

2. Literature Review

Extensive research has been conducted on the structural behavior of shells and their response under seismic loading. Historically, the development of reinforced concrete shell structures can be traced to pioneers such as Joseph Monier, Robert Maillart, and Pier Luigi Nervi, whose innovative works established the foundation for shell design. Later advancements with finite element analysis and computational modeling enabled engineers to simulate complex shell geometries and their nonlinear behavior.

Richard et al. (1960) and Eduardo et al. (1983) contributed significantly to shell theory and finite element formulations. Celebi et al. (1989) and Shenglin Di et al. (1993) extended shell analysis to seismic response and nonlinear laminate shells. Rotter (2005) and Ambroziak (2006) highlighted the need for robust analysis methods and software validation.

In the field of seismic performance-based design, Chopra and Goel (2001) introduced Modal Pushover Analysis (MPA), while Fajfar (2000) developed the N2 method for converting multi-degree-of-freedom (MDOF) models to equivalent single-degree-of-freedom (SDOF) systems. Recent studies (Nie et al. 2014, Menasri and Brahimi 2024) emphasized Incremental Dynamic Analysis (IDA) and fragility curve development for assessing vulnerability. Despite these advances, very limited research exists on the pushover and time history analysis of RC shell structures, indicating a clear research gap.

The literature therefore underscores the importance of developing a systematic methodology tailored for shell structures, which forms the central theme of this paper.

Recent contributions have strengthened the field further. Berger et al. (2020) introduced actively bent concrete shells demonstrating innovative construction techniques. Karhut et al. (2021) presented mathematical and experimental modeling of reinforced concrete protective shell structures, while Zhang et al. (2022) investigated seismic fragility of large-span RC shell roofs through nonlinear dynamic analysis. Chen et al. (2023) examined performance-based seismic design of spatial RC structures with ground motion uncertainties. Kaur and Singh (2021) applied incremental dynamic analysis to RC shell domes for seismic vulnerability assessment. Menasri and Brahimi (2024) developed fragility curves for RC frames under soil-structure interaction effects using SPO2IDA methodology.

These recent works confirm the increasing focus on nonlinear analysis, fragility assessment, and performance-based seismic design for RC shells and spatial structures. However, comprehensive methodologies that integrate multiple approaches for RC shell structures are still limited, reaffirming the relevance of the present study.

3. Methodology and Modeling Approach

The proposed methodology integrates nonlinear static and dynamic procedures for the seismic evaluation of RC shell structures. The steps include:

1. Literature survey and identification of gaps in shell seismic analysis.

2. Selection of geometric and material parameters for shell modeling.

3. Finite element modeling using SAP2000 with layered shell elements to capture concrete and reinforcement behavior.

4. Nonlinear static pushover analysis to establish capacity curves and hinge formation.

5. Conversion of MDOF shell model to SDOF using the N2 method.

6. Nonlinear dynamic time history analysis using selected ground motion records.

7. Incremental Dynamic Analysis (IDA) for seismic demand and capacity prediction.

8. Development of fragility and hazard survival curves for performance-based assessment.

For demonstration, a 36m × 20m RC shell structure with 6m column height is modeled. Discretization is optimized with a 2m × 1m mesh size for accurate yet computationally efficient results. Hinge properties are defined based on FEMA-356 guidelines, and both default and user-defined hinge parameters are used.

In greater detail, the methodology emphasizes the importance of a systematic workflow to capture the nonlinear behavior of RC shell structures. The finite element modeling approach utilizes layered shell elements to represent concrete and reinforcement separately, thus accounting for cracking, yielding, and nonlinear stress-strain relationships. The discretization process was optimized after sensitivity checks to ensure that mesh size influences were minimized. A finer mesh was found to provide more accurate local stress results, while a coarser mesh offered faster computation but at the cost of reduced accuracy.

Furthermore, material properties were defined using nonlinear constitutive models. Concrete was modeled with a stress-strain curve that accounted for cracking and crushing, while reinforcing steel followed an elastic-plastic model with strain hardening. Such details are crucial for simulating the realistic seismic response. Boundary conditions were carefully modeled to reflect fixed column bases, while diaphragm action was simulated to distribute lateral loads uniformly.

The methodological framework was designed not only to evaluate structural response but also to align with performance-based design philosophy, which requires that Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) performance levels be assessed explicitly.

4. Analysis Procedures

Nonlinear static pushover analysis is performed to evaluate the force-deformation capacity. The N2 method is applied to convert the shell's MDOF system into an equivalent SDOF system, simplifying demand-capacity assessment. Time history analysis is conducted using multiple ground motion records, followed by Incremental Dynamic Analysis (IDA) to generate response data across scaled seismic intensities. Fragility curves are derived from IDA results, providing probability-based failure predictions.

These procedures ensure that both global structural performance and localized hinge behavior are captured, enabling a comprehensive evaluation of seismic resilience.

The nonlinear static pushover analysis was executed in SAP2000 by incrementally applying lateral forces until significant hinge formations occurred. The sequence of hinge formation, energy dissipation, and ductility demand were extracted as part of the performance evaluation. Capacity curves generated through pushover analysis were compared against demand spectra derived from ground motion records to identify performance points.

In the N2 method, the transformation of a complex MDOF shell structure into an equivalent SDOF system enabled a simplified yet effective comparison of demand and capacity. This step is critical in translating complex dynamic responses into practical design insights. Time history analysis further complemented pushover results by capturing transient effects of earthquake loading.

The Incremental Dynamic Analysis (IDA) involved subjecting the structure to scaled versions of ground motion records, thereby developing a continuous relationship between seismic intensity and structural demand. This allowed fragility functions to be derived, quantifying the probability of exceeding specific limit states under varying seismic intensities. Hazard survival curves provided another layer of information, transforming fragility results into risk-based performance measures.

5. Results and Discussion

The methodology enables the extraction of critical performance measures such as base shear–displacement relationships, hinge formation sequences, and collapse mechanisms. The SDOF transformation validates the applicability of the N2 method, while IDA results highlight the sensitivity of RC shells to varying seismic intensities. Fragility analysis provides a quantitative framework for risk assessment, showing probabilities of yielding and collapse under different ground motion intensities.

The results demonstrate that RC shell structures possess significant seismic capacity due to their geometry but require rigorous nonlinear analysis for accurate performance prediction. The proposed methodology is thus effective in addressing the inadequacies of conventional elastic design approaches.

Additionally, comparison of pushover curves with time-history and IDA results highlights consistency in predicting global performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The fragility curves developed indicate that RC shells exhibit higher initial stiffness but experience brittle hinge formations at critical locations. The hazard survival curves derived from fragility analysis provide a probabilistic outlook on structural safety, aiding in risk-informed decision making for design and retrofitting. These findings are aligned with performance-based design philosophy and validate the applicability of the proposed methodology in practical scenarios for large-span RC shell roofs.

6. Conclusion and Future Scope

This study presents a comprehensive methodology for seismic analysis of RC shell structures. By integrating pushover, N2 method, time history, IDA, and fragility analysis within a finite element framework, the research provides a performance-based assessment procedure for shell structures. The methodology bridges the gap between conventional seismic analysis techniques and the unique demands of shell geometries.

Future work should focus on experimental validation, consideration of soil-structure interaction, and multi-hazard assessment to further enhance the reliability of seismic performance evaluations for RC shell structures.

The proposed framework bridges the significant research gap that exists between conventional frame-based seismic assessment and the unique demands posed by RC shell structures. Unlike frames, shells rely heavily on membrane action, which requires advanced nonlinear modeling for accurate performance assessment. By integrating multiple approaches—pushover, N2 method, time history, IDA, and fragility analysis—this methodology ensures both global and local behaviors are evaluated.

For future scope, several areas of research are highlighted. Experimental testing of scaled shell models under shake-table conditions would validate the numerical framework and provide calibration data. The role of soil-structure interaction remains underexplored for shell structures and should be studied in depth, especially for large-span roofs where foundation flexibility could significantly influence seismic response. Furthermore, multi-hazard assessment that considers combined effects of earthquakes, wind, and blast loading could broaden the applicability of the methodology. Incorporating advanced materials such as fiber-reinforced concrete and textile-reinforced shells may also improve seismic resilience. Finally, integration of probabilistic performance-based design into building codes for shells is an essential long-term goal.

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