



Stability of Flat Composite Shells with Environmental Reinforcement under Combined Loading Conditions

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Abstract

In this study, the stability of flat composite shells with a thickness of 5 cm and element dimensions of 40 × 200 cm, arranged in a connected grid configuration, was investigated under combined axial, lateral, and external pressure loads. Using the First-Order Shear Deformation Theory (FSDT) and numerical implementation in Abaqus, two environmental reinforcement methods—temperature-dependent and external pressure-dependent—were incorporated into the modeling as controlled variables. The results of nonlinear static analysis indicated that, in the absence of reinforcement, the shells experienced sudden collapse at displacements of 7–11 cm. In contrast, with the application of temperature-induced environmental reinforcement, the yield threshold increased by up to 68%, and the structure exhibited ductile behavior with high energy absorption after passing the linear critical point. This behavior is attributed to the release of anisotropic residual stresses and a more uniform stress distribution across the composite layers. In the model incorporating environmental reinforcement via external pressure, the yield force decreased; however, the overall structural displacement was reduced by 10%, and the minimum von Mises stress decreased by 82%, indicating effective neutralization of bending stresses and enhanced stability in the plastic region. Despite their distinct mechanisms, both reinforcement methods led to a qualitative transformation in structural behavior, shifting from sudden failure to controlled deformation. The analyses demonstrated that environmental reinforcement not only increases load-bearing capacity but also transforms the failure mechanism from localized to progressive and from brittle to ductile. This approach introduces and validates, for the first time in the composite engineering literature, the concept of “environmental reinforcement” as an active design strategy that does not require internal equipment. It provides a foundation for the development of smart roofs, space structures, and systems resistant to combined loading conditions in aerospace, construction, and defense industries.

Keywords: *Stability, flat composite shells, environmental reinforcement, combined loads*

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1. Introduction

The increasing demand for high-performance structural systems in advanced engineering applications has significantly accelerated the development and utilization of composite materials, particularly in the design of shell structures. Composite shells, due to their high strength-to-weight ratio, corrosion resistance, and design flexibility, have become indispensable in aerospace, civil engineering, marine, and defense industries. Classical works on composite mechanics have established the fundamental understanding of anisotropic behavior, laminate theory, and

failure mechanisms in fiber-reinforced materials, forming the backbone of modern composite structural analysis [1, 2]. These foundational studies have demonstrated that the mechanical response of composite shells is highly dependent on fiber orientation, stacking sequence, and material anisotropy, which collectively govern stiffness distribution, load transfer, and stability characteristics.

From a structural mechanics perspective, the stability of shell structures has long been a critical concern due to their susceptibility to buckling under compressive and combined loading conditions. Classical stability theories, particularly those developed by Stephen Timoshenko, have provided



analytical frameworks for understanding elastic instability in thin-walled structures [3]. However, the extension of these theories to composite shells introduces additional complexity due to material heterogeneity and coupling effects between bending, stretching, and shear deformations. To address these complexities, higher-order theories such as the First-Order Shear Deformation Theory (FSDT) have been widely adopted, enabling more accurate prediction of transverse shear effects and overall deformation behavior in moderately thick composite shells [4].

In recent decades, extensive research has focused on the nonlinear behavior and stability of composite shells subjected to combined loading conditions. Nonlinear analysis has revealed that the interaction between axial, lateral, and pressure loads significantly influences the critical buckling load and post-buckling response of these structures. Studies have shown that composite shells often exhibit complex instability phenomena, including snap-through buckling, mode interaction, and progressive damage evolution [5, 6]. Furthermore, the presence of defects such as cracks or imperfections can drastically reduce the load-bearing capacity and alter the failure mechanisms, emphasizing the need for robust modeling approaches [7].

Advancements in computational mechanics and numerical methods have enabled more detailed and accurate simulation of composite shell behavior. Multiscale modeling approaches have been developed to capture the interaction between microstructural features and macroscopic structural response, providing deeper insight into failure mechanisms and performance optimization [8, 9]. These methods allow engineers to incorporate material heterogeneity, interfacial effects, and damage evolution into predictive models, thereby enhancing the reliability of structural assessments. Additionally, the integration of machine learning techniques in material modeling has opened new avenues for optimizing composite structures and predicting their behavior under complex loading scenarios [10].

Another important dimension in the study of composite shell stability is the influence of environmental factors such as temperature, moisture, and external pressure. These factors can significantly alter material properties, induce residual stresses, and affect the overall structural performance. For instance, thermal loads can generate significant in-plane stresses due to differential expansion between layers, which may either stabilize or destabilize the structure depending on the boundary conditions and material configuration [11]. Similarly, environmental pressure, particularly in marine and offshore applications, plays a

critical role in determining the stability and strength of shell structures [12]. The interaction between environmental loads and mechanical loads further complicates the analysis, necessitating comprehensive frameworks that can account for coupled thermo-mechanical effects.

The concept of smart and adaptive composite structures has emerged as a promising approach to address these challenges. Smart composites, which incorporate sensing and actuation capabilities, can actively respond to environmental changes and loading conditions, thereby enhancing structural performance and resilience [13]. In parallel, recent studies have explored the use of hybrid composite systems and advanced reinforcement techniques to improve the mechanical properties and durability of structural elements. For example, the integration of fiber-reinforced polymers with traditional materials has been shown to significantly enhance seismic performance and load-bearing capacity [14, 15]. Moreover, the development of nanocomposite materials has introduced new possibilities for tailoring material properties at the nanoscale, leading to improved strength, stiffness, and environmental resistance [16, 17].

Despite these advancements, a critical gap remains in the systematic incorporation of environmental effects as active design parameters rather than passive loading conditions. Most existing studies treat environmental factors such as temperature and pressure as external disturbances that influence structural behavior, without considering their potential role as controllable reinforcement mechanisms. However, recent research suggests that environmental conditions can be strategically manipulated to enhance structural performance. For instance, controlled thermal loading can induce beneficial residual stress redistribution, while external pressure can improve stability by counteracting tensile stresses in critical regions [18, 19]. These findings indicate that environmental factors can be leveraged as design tools to actively modify the mechanical response of composite shells.

Furthermore, the interaction between environmental effects and structural behavior is inherently nonlinear and highly dependent on material properties, geometry, and loading conditions. This complexity necessitates the development of integrated analytical–numerical frameworks capable of capturing coupled effects and predicting system behavior with high accuracy. Existing models often focus on isolated aspects of the problem, such as thermal effects or mechanical loading, without fully addressing their combined impact on stability and failure mechanisms. As a result, there

is a need for comprehensive methodologies that can simultaneously account for multiple loading components and environmental influences within a unified framework.

In addition to theoretical and computational challenges, practical considerations such as manufacturability, cost efficiency, and structural reliability further complicate the design of composite shell systems. Engineers must balance these factors while ensuring that the structures meet performance requirements under diverse operating conditions. The development of innovative design strategies that integrate environmental reinforcement concepts can provide new opportunities for optimizing structural performance without significantly increasing complexity or cost [20, 21].

Therefore, the present study aims to develop a comprehensive analytical–numerical framework for evaluating the stability of flat composite shells under combined loading conditions, while introducing and validating the concept of environmental reinforcement as an active design strategy that enhances structural performance and alters failure mechanisms.

2. Methodology

In this study, considering the gaps identified in the literature, a comprehensive mathematical–numerical framework was developed to analyze the stability of flat composite shells under combined loading conditions. The primary innovation of the research methodology lies in the simultaneous consideration of four loading components—axial load, lateral load, environmental pressure, and temperature variations—as well as the incorporation of the environment as an active reinforcing factor within the analytical model.

In the first step, the theoretical foundation of the analysis was established based on the First-Order Shear Deformation Theory (FSDT), enabling accurate modeling of shear deformations, normal rotations, and coupled bending–shear behavior. This selection was made due to the high length-to-thickness ratio of the shells and the necessity to achieve a balance between computational efficiency and modeling accuracy.

Subsequently, the governing equations of shell behavior were derived using the principle of virtual work. This approach allowed for the simultaneous inclusion of combined loads, initial stresses induced by environmental conditions, and prestressing effects. Thermal- and moisture-induced stresses were introduced into the equilibrium

equations as initial stresses (pre-stress), thereby quantitatively incorporating environmental effects into the model.

Thermal effects, as one of the key components of environmental reinforcement, were modeled by defining thermal strains and stresses in the different composite layers. The temperature gradient between the upper and lower surfaces of the shell was represented as an equivalent thermal load in the governing equations, enabling the analysis of residual stress release or redistribution.

To analyze strain and displacement behavior, the kinematic relations of FSDT were defined, including in-plane displacements, transverse displacement, and normal rotations. From these relations, in-plane, bending, and shear strains were derived, and equivalent layer stiffness matrices were constructed based on fiber orientation and material anisotropy.

In the numerical phase, the finite element software Abaqus was selected as the solution tool. Shell elements based on Reissner–Mindlin theory (such as S4R) were employed to model FSDT behavior. The composite layup, fiber orientations, and thickness of each layer were defined individually to accurately simulate the behavior of multilayer composite roofs.

To implement thermal environmental reinforcement, the analysis was conducted through multiple thermo-mechanical steps. First, heating and cooling processes were applied to induce or release residual stresses, followed by the application of mechanical loading in a separate step. This multi-stage analysis enabled evaluation of the effect of temperature variations on the critical buckling load.

In the second environmental reinforcement mechanism, controlled external pressure was defined as a uniform surface load. This external pressure was applied simultaneously with internal pressure and other loads, followed by a linear buckling analysis based on initial stress (pre-stressed buckling). This method allowed assessment of the role of environmental pressure in increasing the critical load.

In the third mechanism, the effect of localized moisture was modeled by defining mechanical properties dependent on a field variable. Using the field variable feature in the software, a reduction in elastic modulus was applied in critical regions to investigate stress redistribution and stress concentration reduction. This approach incorporated moisture effects indirectly but effectively into the numerical model.

Finally, stability analysis was conducted using linear buckling methods and evaluation of instability modes, and the results of different scenarios (with and without environmental reinforcement) were compared. This combined analytical–numerical approach enabled a comprehensive evaluation of the effects of combined loads and environmental reinforcement mechanisms, providing an innovative framework for the active design of flat composite shells.

In this study, the model of flat composite shells was simulated on load-bearing walls, and their behavior under combined loading conditions was investigated both with and without environmental reinforcement. For the walls, micro-modeling of masonry materials, including brick and mortar, was employed, while for the flat composite shell, a macro-modeling or constitutive modeling approach was used to realistically capture the interaction between different materials and the structural geometry. The shell dimensions, layer thicknesses, and stacking sequence were defined according to the physical and mechanical properties of composite and masonry materials, and the elastic parameters of the materials—dependent on temperature and moisture—were incorporated into the ABAQUS model to simulate environmental effects.

The model loading included dead and live loads, axial loads, environmental pressures, and dynamic effects such as earthquakes, while boundary conditions were defined as fixed. Loads were applied cyclically using the Load and Amplitude modules in ABAQUS, and analyses included

nonlinear static (Static General) and explicit dynamic methods. The model mesh was generated with sufficient refinement to accurately capture stress and strain distributions, and the integration of detailed material modeling with realistic loading conditions enabled the investigation of nonlinear structural behavior and the effects of environmental reinforcement.

For model validation, the simulation results were compared with the data from Pourian’s study, and an acceptable agreement was observed between the applied accelerations and the structural response. This comparison confirms the validity of the modeling and analysis approach in ABAQUS and demonstrates that the present model is capable of accurately predicting the behavior of flat composite shells under combined loading conditions and various environmental scenarios. This validation provides a foundation for subsequent analyses and the implementation of environmental reinforcement mechanisms, including temperature variation, external pressure, and localized moisture distribution.

3. Findings and Results

The results of the nonlinear static analysis and capacity curves are presented below. The results of the nonlinear static analysis of the flat composite shell model without environmental reinforcement using the temperature-dependent function are shown in Figure 1.

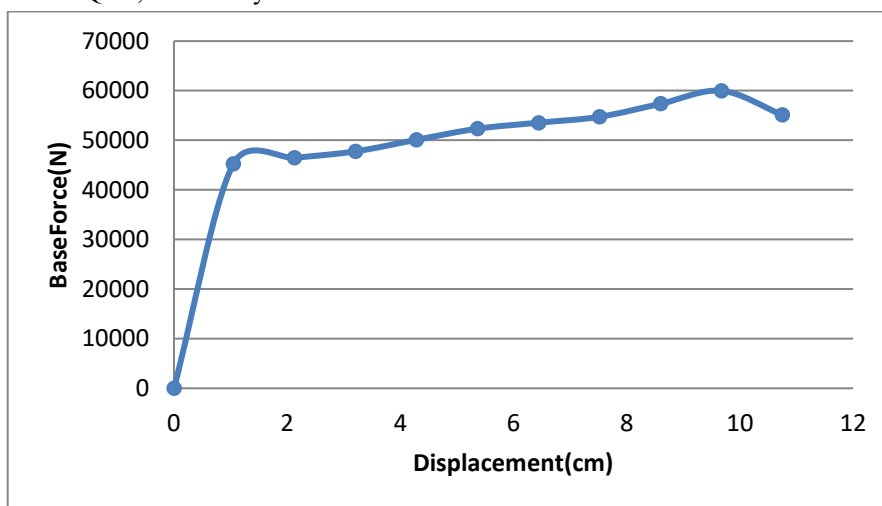


Figure 1. Results of the flat composite shell model analysis without environmental reinforcement using a temperature-dependent function

Figure 1 illustrates that, in this model, the frame reaches the section yield point at a displacement of 7 cm with a base

force of 54 tons. Furthermore, the structure experiences damage at a displacement of 10 cm and approaches the verge of collapse.

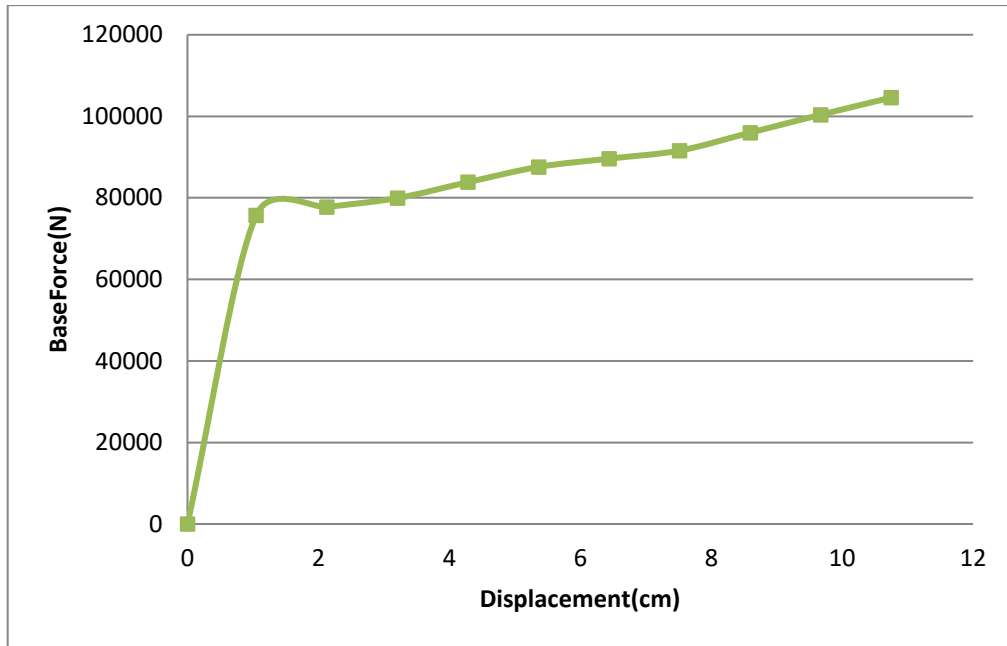


Figure 2. Results of the flat composite shell model analysis with environmental reinforcement using a temperature-dependent function

In the flat composite shell model with environmental reinforcement and a temperature-dependent function, the structure reaches the yield point at a displacement of 7 cm

with a force of 91 tons. In this case, due to environmental reinforcement, the structure exhibits positive strain hardening and does not collapse.

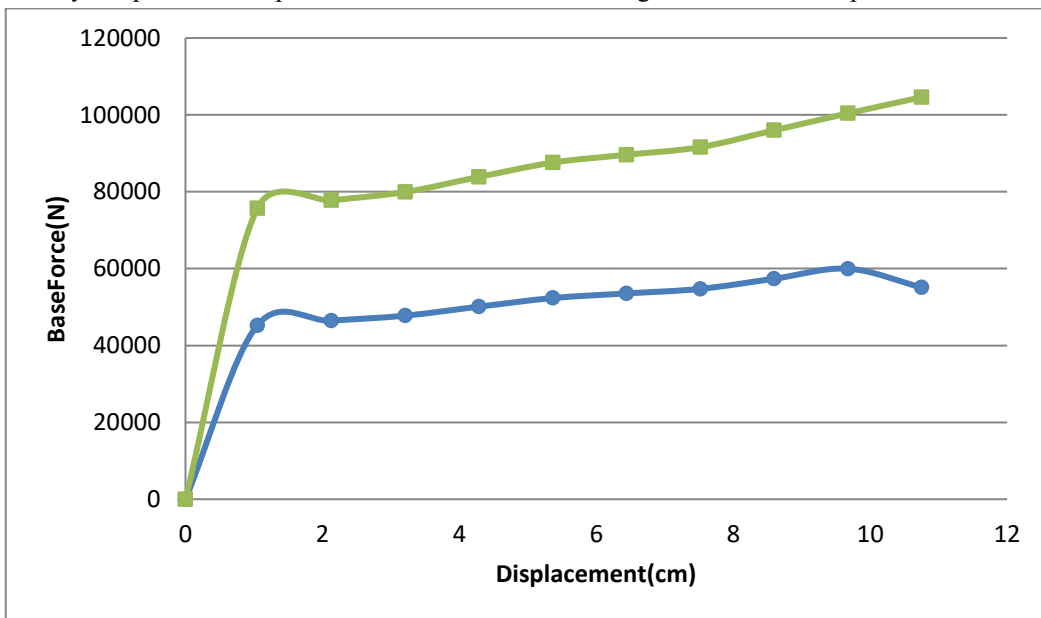


Figure 3. Comparison of environmental reinforcement in the wall with the flat composite shell (Blue: Flat composite shell without environmental reinforcement; Green: Flat composite shell with environmental reinforcement)

As shown in Figure 3, nonlinear static analysis of the flat composite shell with temperature-dependent environmental reinforcement indicates that the reinforced model demonstrates higher energy absorption capacity and improved performance. In contrast, the unreinforced model undergoes collapse. Environmental reinforcement significantly enhances energy absorption.

In the model without environmental reinforcement:

Temperature and moisture variations during manufacturing or operation generate anisotropic residual stresses in the composite layers. These stresses are typically tensile in the fibers and compressive in the matrix, weakening local critical regions such as fiber–matrix

interfaces. Upon application of external loading, these initial stresses combine with the applied load, causing the total stress to rapidly reach the failure threshold and resulting in sudden collapse.

In the model with environmental reinforcement:

By increasing the temperature to an optimal level (e.g., 70°C prior to loading), the matrix softens and tensile residual stresses in the fibers are released. As a result, the fibers begin to carry the load in a stress-free initial state. Consequently, the input energy is dissipated through elastic deformation and uniform strain distribution rather than stress concentration and crack initiation.

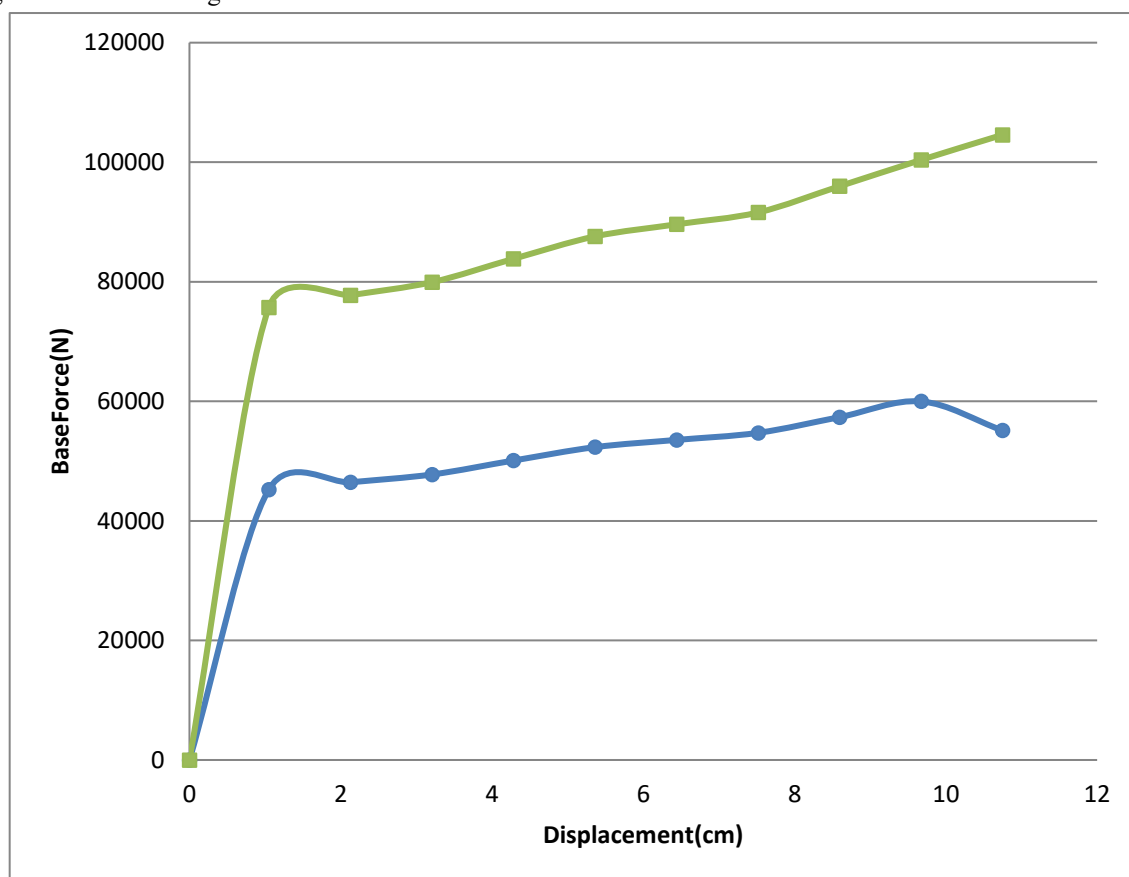


Figure 4. Results of the model analysis without a flat composite shell and without environmental reinforcement (Blue: Flat composite shell without environmental reinforcement; Green: Flat composite shell with environmental reinforcement)

Figure 4 shows the results of the masonry model without a flat composite shell and without environmental reinforcement. In this model, the frame reaches the yield point at a displacement of 7 cm with a base force of 48 tons. Additionally, the structure experiences damage at a displacement of 8.5 cm and approaches collapse.

The results of the nonlinear static analysis of the flat composite shell structure with environmental reinforcement using the external pressure function, as well as without considering it, are presented in Figure 5.

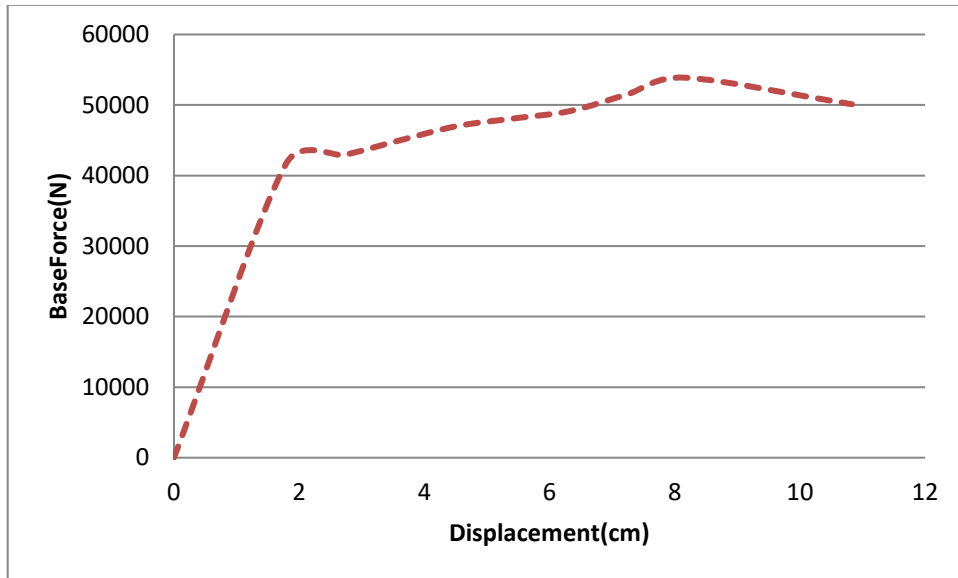


Figure 5. Results of the flat composite shell model without environmental reinforcement using an external pressure function

Figure 5 shows that the roof reaches the yield point at a displacement of 6 cm with a base force of 81 tons. The structure experiences damage at a displacement of 11 cm and approaches collapse.

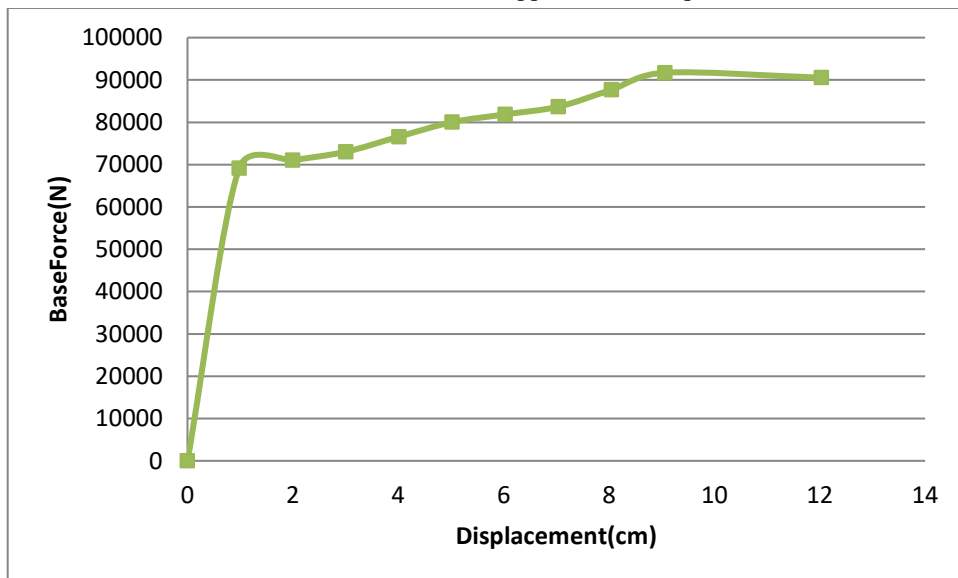


Figure 6. Results of the flat composite shell roof model with environmental reinforcement using an external pressure function

In the flat composite shell roof model with environmental reinforcement and an external pressure function, the structure reaches the yield point at a displacement of 9.5 cm with a force of 47 tons.

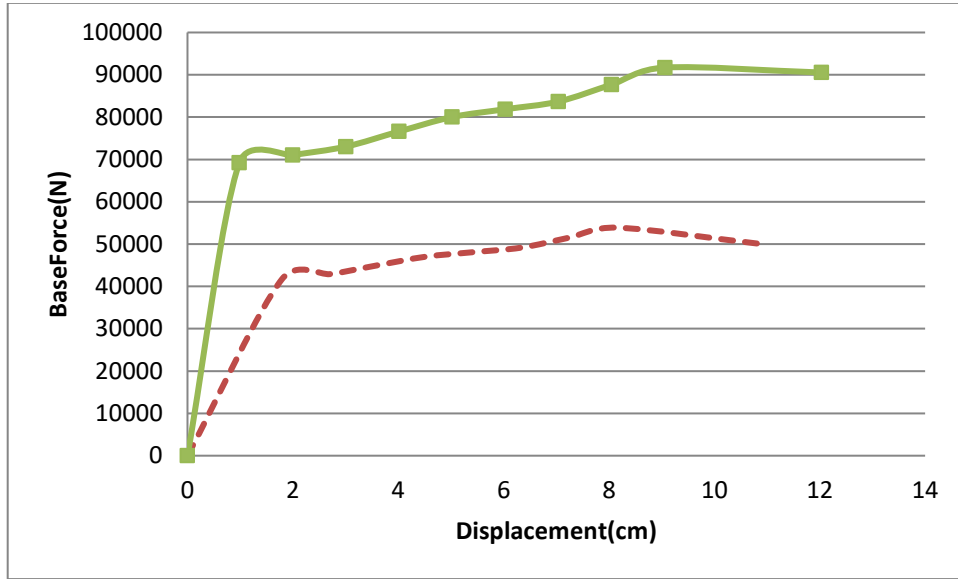


Figure 7. Comparison of the effect of the external pressure function on the flat composite shell element

As illustrated in Figure 7, in the model with the external pressure function, seismic energy absorption decreases compared to the model without environmental reinforcement. However, roof displacement is reduced by approximately 10% in the reinforced model. The stiffness in the elastic region, as indicated by the slope of the curve, decreases in the model with the external pressure function;

however, in the plastic region, or in terms of effective stiffness, the model with external pressure reinforcement exhibits an increase.

Stress Contour Results

The von Mises stress contour results for the investigated models are presented below.

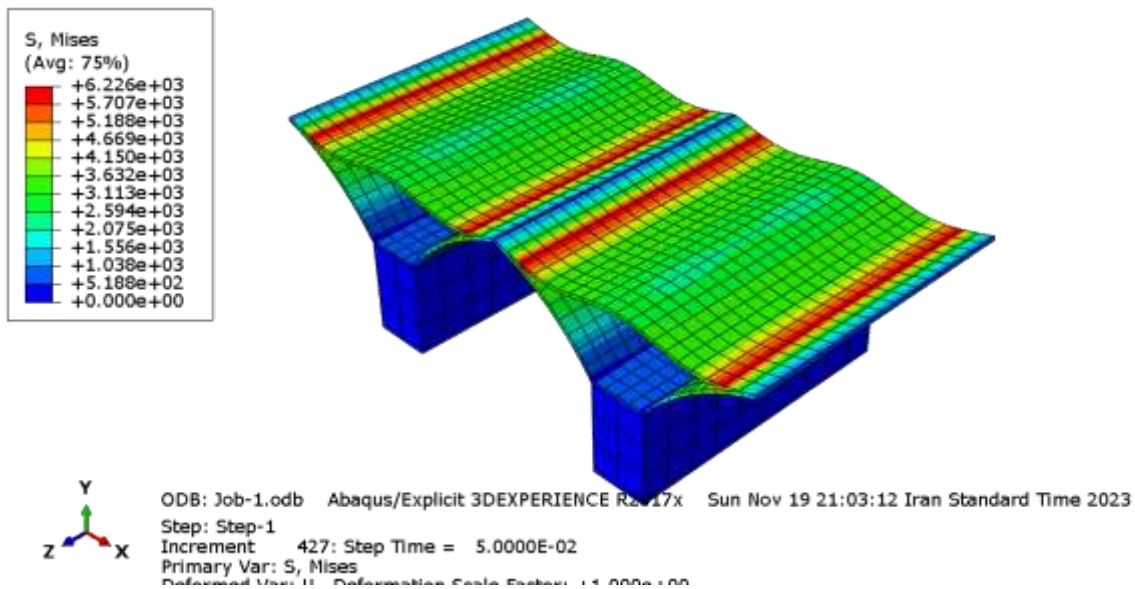


Figure 8. Stress contour results for the roof structure without environmental reinforcement and without external pressure function

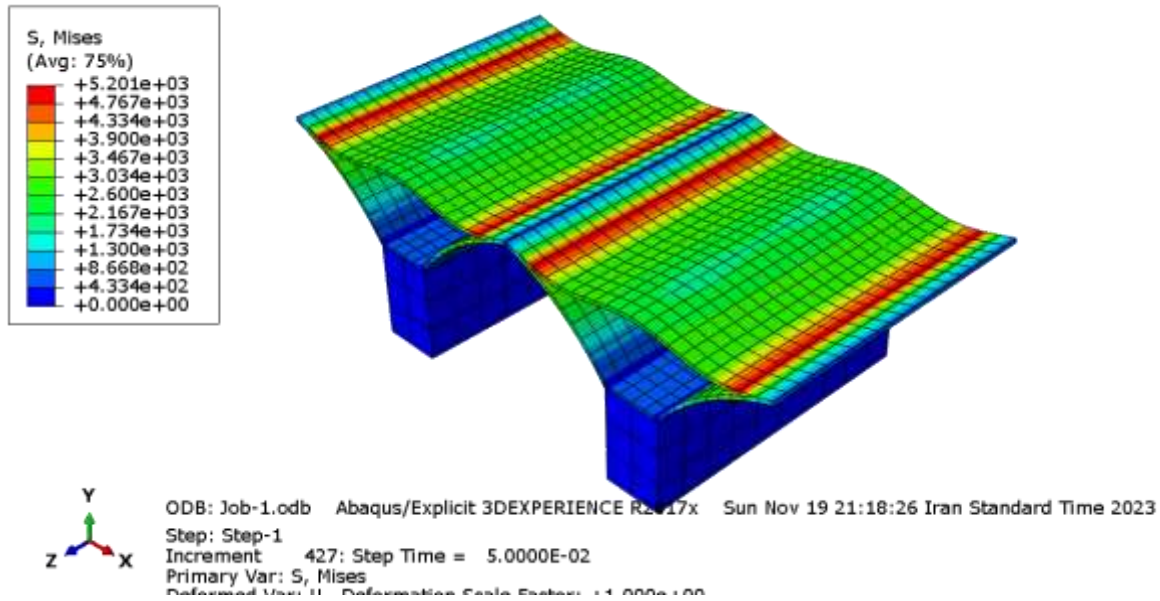


Figure 9. Stress contour results for the roof structure with environmental reinforcement using an external pressure function

The results of the shell structure models indicate that the external pressure function reduces the maximum von Mises stress by 82% compared to the model without external pressure, while it does not alter the locations of stress concentration. The highest stresses occur along the curved perimeter of the modeled roof. Therefore, the external pressure function, as a method of environmental reinforcement in flat composite shell structures, can be effective in reducing roof displacement.

4. Discussion and Conclusion

The findings of the present study provide a comprehensive understanding of the nonlinear structural behavior of flat composite shells under combined loading conditions, particularly highlighting the transformative role of environmental reinforcement mechanisms. The results demonstrated that, in the absence of environmental reinforcement, the flat composite shell exhibited a relatively low yield threshold and experienced sudden collapse at moderate displacement levels. Specifically, the structure reached its yield point at approximately 7 cm displacement with a base force of 54 tons and approached collapse at around 10 cm displacement. This behavior is consistent with classical instability theories, which emphasize the susceptibility of thin-walled structures to abrupt buckling under compressive and combined loads [3]. Moreover, the observed brittle failure mode aligns with prior studies indicating that composite shells, when subjected to

combined loading without adequate stress redistribution mechanisms, tend to exhibit localized failure and rapid degradation of load-carrying capacity [6, 7].

In contrast, the implementation of environmental reinforcement through temperature-dependent mechanisms significantly enhanced the structural performance. The results indicated an increase in the yield force to approximately 91 tons at the same displacement level, representing a substantial improvement in load-bearing capacity. More importantly, the structural response transitioned from a brittle failure mode to a ductile behavior characterized by positive strain hardening and increased energy absorption. This shift can be explained by the release of anisotropic residual stresses within the composite layers, which otherwise contribute to premature failure. Similar observations have been reported in the literature, where thermal effects were shown to influence stress redistribution and delay the onset of instability in composite shells [5, 11]. The ability of thermal loading to modify internal stress states and enhance structural resilience further supports the concept of environmental reinforcement as an active design strategy.

The mechanism of residual stress relief plays a critical role in explaining the improved performance of the thermally reinforced model. In the unreinforced state, manufacturing-induced residual stresses—typically tensile in fibers and compressive in the matrix—create localized weaknesses that accelerate failure under external loading. The application of controlled thermal conditions leads to

matrix softening and relaxation of these stresses, allowing the fibers to carry loads more efficiently and uniformly. This phenomenon is consistent with multiscale analyses of composite materials, which highlight the importance of microstructural stress distribution in determining macroscopic behavior [8, 20]. Consequently, the observed increase in energy absorption capacity can be attributed to the reduction of stress concentrations and the promotion of uniform deformation across the composite layers.

The results obtained from the external pressure-based environmental reinforcement mechanism revealed a different but equally significant influence on structural behavior. Unlike thermal reinforcement, which increased the yield force, the application of external pressure resulted in a reduction in yield force while simultaneously decreasing overall displacement and stress levels. The reduction in maximum von Mises stress by approximately 82% indicates a substantial mitigation of stress concentration effects. This behavior can be interpreted as the result of compressive confinement provided by the external pressure, which counteracts tensile stresses and stabilizes the structure in critical regions. Similar findings have been reported in studies on composite shells subjected to hydrostatic pressure, where external pressure was shown to enhance stability and delay buckling under certain conditions [12, 19].

Despite the reduction in yield force, the decrease in displacement and the increase in effective stiffness in the plastic region suggest that external pressure reinforcement contributes to improved post-yield performance. The observed reduction in elastic stiffness, as indicated by the slope of the load–displacement curve, may initially appear unfavorable; however, this effect is offset by the enhanced stability in the plastic region, where the structure demonstrates increased resistance to progressive deformation. This behavior aligns with nonlinear analyses of composite shells, which indicate that post-buckling strength and deformation capacity are critical factors in determining overall structural performance [5, 6].

The comparative analysis between reinforced and unreinforced models further underscores the effectiveness of environmental reinforcement in altering failure mechanisms. In the absence of reinforcement, the structure exhibited localized damage and abrupt collapse, whereas in the reinforced models, failure occurred in a more distributed and gradual manner. This transition from brittle to ductile behavior is particularly important in engineering applications, as it enhances structural safety by providing

warning before failure and allowing for energy dissipation. Such behavior is consistent with the principles of composite material design, where controlled damage mechanisms are often preferred to prevent catastrophic failure [2, 21].

The integration of environmental factors as active design parameters represents a significant departure from traditional approaches, where these factors are typically treated as external disturbances. The present study demonstrates that temperature and pressure can be strategically utilized to improve structural performance, thereby expanding the design space for composite shell structures. This concept is closely related to the emerging field of smart composites, which aim to achieve adaptive behavior through the interaction between material properties and environmental conditions [13]. By incorporating environmental reinforcement mechanisms into the design process, it is possible to develop structures that not only withstand adverse conditions but also exploit them to enhance performance.

Furthermore, the findings highlight the importance of considering combined loading conditions in structural analysis. The interaction between axial, lateral, and environmental loads creates complex stress states that cannot be accurately captured using simplified models. Advanced numerical methods, such as those employed in this study, are essential for capturing these interactions and predicting structural behavior with high fidelity. The use of finite element analysis, combined with appropriate theoretical frameworks such as FSDT, enables detailed investigation of deformation patterns, stress distribution, and stability characteristics [4].

The results also have implications for the design of hybrid and advanced composite systems. Recent developments in composite technology, including the use of hybrid materials and nanocomposites, have demonstrated significant potential for improving structural performance [15, 16]. The concept of environmental reinforcement can be integrated with these advancements to further enhance the capabilities of composite structures. For instance, the use of temperature-responsive materials or pressure-adaptive systems could enable real-time control of structural behavior, leading to more efficient and resilient designs.

Overall, the findings of this study contribute to the growing body of knowledge on the stability and performance of composite shell structures. By demonstrating the effectiveness of environmental reinforcement mechanisms, the study provides a novel perspective on the role of environmental factors in structural design. The results not

only validate existing theoretical and numerical models but also extend their applicability by introducing new design strategies that leverage environmental interactions. This approach has the potential to significantly impact the design and analysis of composite structures in various engineering fields, including aerospace, civil engineering, and marine applications.

One limitation of this study is the reliance on numerical simulation without extensive experimental validation. Although the results were compared with existing data and showed good agreement, experimental studies are necessary to fully confirm the effectiveness of environmental reinforcement mechanisms under real-world conditions. Another limitation is the assumption of idealized boundary conditions and material properties, which may not accurately represent all practical scenarios. Additionally, the study focused primarily on specific types of loading and reinforcement mechanisms, and further investigation is required to explore a wider range of conditions and configurations.

Future research should focus on experimental validation of the proposed environmental reinforcement strategies, including laboratory testing of composite shell specimens تحت controlled thermal and pressure conditions. Moreover, the development of advanced material models that incorporate damage evolution, viscoelastic effects, and environmental degradation would enhance the accuracy of predictions. Investigating the interaction between multiple environmental factors, such as temperature, moisture, and chemical exposure, could provide a more comprehensive understanding of structural behavior. The integration of machine learning techniques for optimizing reinforcement strategies and predicting performance under complex loading scenarios also represents a promising area for future research.

From a practical perspective, the findings of this study suggest that environmental reinforcement can be effectively utilized in the design of advanced structural systems. Engineers can leverage temperature control, external pressure, and moisture distribution to enhance the performance of composite shells without significantly increasing structural complexity. This approach can be particularly beneficial in applications where weight reduction, durability, and resilience are critical considerations, such as aerospace structures, offshore platforms, and high-performance buildings. The adoption of environmental reinforcement strategies has the potential to improve structural safety, extend service life, and reduce

maintenance costs, thereby contributing to more sustainable and efficient engineering solutions.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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