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Parametric Analysis of the Static Behavior of Long Cylindrical Concrete Thin Shells under Self-Weight Loading

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ABSTRACT

In this study, a comprehensive parametric investigation of the static behavior of long cylindrical concrete thin shells subjected to self-weight loading is presented. The analysis was conducted using the ANSYS software, and the effects of three factors, namely span, central angle, and thickness, were systematically examined. It was observed that the central angle, thickness, and span significantly influenced the shells' performance. Specifically, larger central angles led to increased deflection under loading, and thicker shells demonstrated enhanced resistance to buckling. Furthermore, the shell's span was found to have a notable impact on its overall behavior, with longer shells exhibiting greater deflection compared to shorter ones. The obtained results were compared with a numerical model from previous research, showing a difference of less than 5%. This close agreement lends credence to the study's conclusions and interpretations. The findings of this investigation contribute valuable insights to the field of cylindrical concrete thin shells, providing a solid foundation for future research and practical applications.

1. INTRODUCTION

Concrete structures are extensively employed in modern construction, and comprehending their behavior under various loading conditions is vital for ensuring their safety and longevity. One type of concrete structure that has attracted significant attention in recent years is the long concrete thin shell, often utilized in the construction of large-span structures such as roofs, domes, and vaults. The behavior of these structures is intricate, and their structural performance is heavily influenced by their geometric and material properties.

Cylindrical reinforced concrete shells are a common choice for covering expansive spaces, with long ($L/R \geq 2.5$) and short ($L/R < 2.5$) shells being the two primary types [1]. Long shells are typically used for factory roofs, while short shells are suitable for aircraft hangars. As the L/R ratio decreases, the ultimate load capacity of reinforced concrete shell models increases; however, short shells exhibit less ductile behavior compared to long shells [2].

In recent years, numerous researchers have investigated the static behavior of cylindrical concrete thin shells using finite element analysis. This paper presents a review of recent studies in this area, their respective methodologies, and limitations. Lu and Jing [3] explored the structural feasibility of an arched shell roof structure system for a warehouse measuring 36m×20m. Numerical simulations were performed using the ANSYS finite element method for an arched shell roof structure with a thickness of 150mm. The results demonstrated that the deformation and stress met specification requirements, indicating that the selection of an arched shell roof system is feasible. Lende and Talikoti [4] conducted a parametric study by analyzing multiple cylindrical shells for different parameters using the computer analysis program SAP 2000. They examined two-dimensional models with span lengths of 10m and 12m and a length-to-width ratio of 3, altering the radius and shell thickness. The study concluded that the structural behavior differed across the dimensional models.

David [2] presented a nonlinear finite element analysis of reinforced concrete cylindrical shells and investigated their behavior under monotonically increasing loads. The three-dimensional model of six small-scale experimental shells with length-to-radius ratios ranging from 0.84 to 5.0 was analyzed using the ANSYS computer code. The nonlinear response was traced throughout the entire load range up to failure, revealing that cracking occurs at working load levels, with a subsequent reduction in shell stiffness. Increasing loads led to varying failure modes, from beam failure in long shells to combined longitudinal and transverse cracking in intermediate-length shells and abrupt diagonal with limited transverse cracking in short shells.

Sharei et al. [5] performed an experimental investigation on the load-bearing behavior of lightweight, textile-reinforced concrete barrel vault shells and compared test results with nonlinear finite element simulation results. Do et al. [6] conducted an ANSYS numerical simulation study to examine the stress and strain states of double-layer doubly curved concrete shell roofs. They changed initial parameters, such as layer thickness, the location of the steel fiber concrete layer within the structure, and the steel fiber content contained in the concrete shell for a 3000×3000 mm shell. The experimental and simulation results were verified against each other, and it was found that the optimal bearing capacity of the curved shell roof was achieved when the steel fiber concrete layer was placed below the normal concrete layer, the percentage of steel fibers contained in the concrete was 2%, and the thickness was optimal. Barbhuiya [7] conducted stress analysis on long thin cylindrical shells using Fourier series and Schorer's theory, proving that shell structures exhibit both membrane and bending behavior.

While these studies have significantly contributed to our understanding of the behavior of cylindrical concrete thin shells, their scope is limited, and further research is necessary to examine the behavior of shells under varying conditions. The proposed parametric study aims to fill this gap by considering the influence of three factors—span, central angle, and thickness—on the behavior of cylindrical thin shells using ANSYS software for finite element analysis.

2. SHELL GEOMETRY

The geometric parameters of circular shell structures are the shell span (*S*), length (*L*), thickness (*T*), radius of curvature (*R*) and the semi central angle (*Ø*). There is a geometric relationship between span, radius of curvature and semi central angle as shown in Eq. (1):

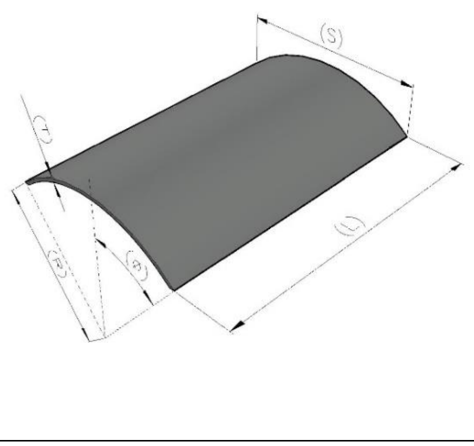
$$R = \frac{S}{2 \sin \emptyset} \tag{1}$$

Hence, the curvature of a surface at a given point can be described by the formula 1/R, where *R* is the radius of curvature at that point [8], Eq. (1) becomes:

$$\frac{1}{R} = \frac{2 \sin \emptyset}{S} \tag{2}$$

Table 1. List of parameters and their values in the finite element method calculations

Parameter	Symbol	Maximum	Minimum	Unit
Shell span	S	30	10	m
Shell length	L	75	25	m
Shell thickness	T	0.100	0.070	m
Semi central Angle	Ø	45	30	Degree



The parameters used in this study for the cylindrical concrete thin shell are summarized in Table 1. The semi-central angle was varied between 30 and 45 degrees, while the thickness was between 70 and 100 mm. These values of semi-central angle and thickness were chosen based on common practices in shell construction, as described in the study [9]. The study also considered three spans, 10m, 20m and 30m with a fixed ratio of length to span (L/S) of 2.5. The parametric study analysed the influence of these parameters on the behaviour of the cylindrical concrete thin shell.

3. MATERIAL PROPERTIES

The material of choice for the cylindrical thin shell structures in this study is concrete. The design properties for concrete were selected in accordance with Chapter 2 of ACI 318.2-19 (Building requirements for concrete shells), which specifies that the minimum compressive strength of concrete at 28 days must be 3000 psi (21 MPa) [10]. In this study, a compressive strength of 30 MPa was assumed.

The modulus of elasticity of concrete (E_c) was calculated using the equation provided in Chapter 19 of ACI 318-19 [11], which states that $E_c=4700\sqrt{f'c}$ (in MPa). With a compressive strength of $f'_c=30$ MPa, the modulus of elasticity was determined to be 2.6×10^4 MPa.

The Poisson's ratio (v) for concrete, which represents the ratio of transverse to longitudinal strains, ranges between 0.15 and 0.20 [12]. In this study, a Poisson's ratio of 0.20 was assumed.

A summary of the material properties used in the finite element analysis models can be found in Table 2.

Table 2. Summary of the concrete properties in the finite element calculations

Property	Value
Grade of concrete	30 (MPa)
Modulus of elasticity	2.6×10^4 (N/mm^2)
Poisson ratio	0.2

4. ELEMENT SELECTION (8 NODE SHELL93)

The ANSYS element library contains more than sixty elements for static and dynamic analyses but in this case Shell93 element is chosen to solve the problem [13].

Shell93 is an 8-node structural finite element in the program element library. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. The deformation shapes are quadratic in both in-plane directions (Figure 1). The element has plasticity, stress stiffening, large deflection, and large strain capabilities [13].

The geometry, node locations, and the coordinate system for this element are shown in Figure 2. The element is defined by eight nodes, four thicknesses, and the orthotropic properties. A triangular-shaped element may be formed by defining the same node number for nodes K, L and O [2].

Pressures may be input as surface loads on the element faces as shown by the circled numbers on Figure 1. Positive pressures act into the element. Edge pressures are input as force per unit length.

Nodes, degrees of freedom, thickness as real constants, modulus of elasticity, Poisson's ratio, density as material properties are element inputs [13].

The solution output associated with the element is in two forms; one is nodal solution the other is element solution. Several items are illustrated in Figure 2. Printout includes the moments about the x face (MX), the moments about the y face (MY), and the twisting moment (MXY). The moments are calculated per unit length in the element coordinate system.

The element stress directions and force resultants (NX, MX, TX, etc.) are parallel to the element coordinate system.

Volume of elements, stresses, strains, moments, displacements are some outputs of shell93 [13].

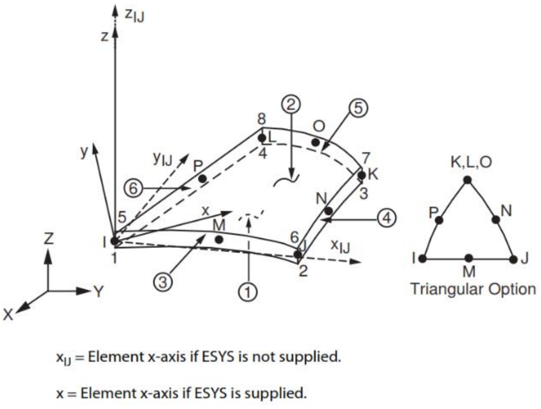


Figure 1. Geometry of shell93 finite element in ANSYS [13]

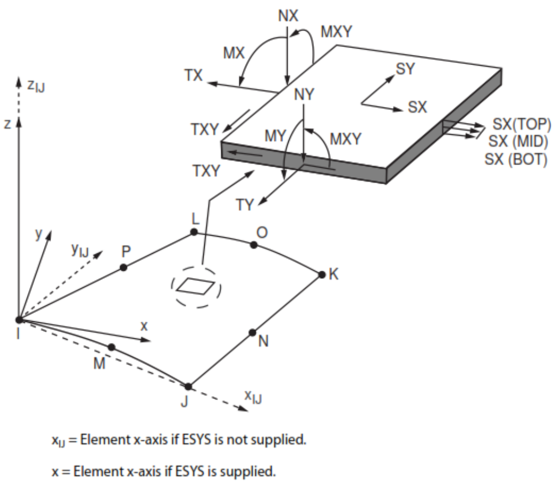


Figure 2. Stress output of shell93 finite element in ANSYS [13]

5. LINEAR STATIC ANALYSIS

A linear static analysis is an analysis where a linear relation holds between applied forces and displacements. In practice, this is applicable to structural problems where stresses remain in the linear elastic range of the used material. Concrete shell structures show high structural efficiency to resist the applied static loads through their membrane action. Therefore, it can be constructed thin, and the loading from the self-weight is relatively low.

The shape of a shell structure is typically established so that it performs efficiently under gravity loads, transmitting to the foundation mainly through membrane action over the shell surface. In this study, the focus is solely on the behaviour of concrete shells under the influence of their self-weight.

The purpose of the research is to investigate the impact of geometric parameters on the performance of concrete shell structures. Since the stresses generated by the self-weight are within the elastic range of the concrete material, a linear static analysis is appropriate to capture the behaviour of the structure. The investigation of collapse loads and nonlinear behaviour (via nonlinear static analysis) falls outside the scope of this study.

6. RESULTS AND DISCUSSION

The purpose of this research is to perform a comparative parametric analysis of cylindrical shell structures of varying lengths using the ANSYS analysis software. A linear static analysis approach was employed, taking into consideration only the self-weight of the cylindrical shells.

6.1 Model description

The current study focuses on the structural behaviour of long cylindrical concrete roof shells with three different spans of 10m, 20m, and 30m and a span to length ratio of 2.5 for all spans. The semi-central angle of these roof shells ranges from 30 to 45 degrees, and the thickness of the shell's ranges from 70mm to 100mm. The material properties considered in the study include a compressive strength of concrete equal to 30 MPa, a modulus of elasticity equal to 26000 MPa, and a Poisson's ratio of 0.2. The boundary conditions assumed for the roof shells are simple support from two sides and freedom from the other sides. The objective of the study is to investigate the effect of various parameters on the structural behaviour of these roof shells and to develop a comprehensive understanding of their behaviour under load.

6.2 Validation of results

To validate the finite element models developed in this study, the results of the analysis were compared with results with other numerical model from reference number [3] for a long cylindrical concrete thin shell. The numerical model was a cylindrical roof with span of 20m and length of 36m. The thickness of shell is 150mm. The semi central angle is 30 degrees. Provided a comparison of the maximum vertical deflection.

According to the model validation results, the previous paper's maximum vertical deflection was recorded as 1.95mm, while the current paper's model showed a deflection of 1.877mm. Both models are in close agreement, with a difference of less than 5%, indicating the consistency and reliability of the models. This further supports the validity of the study's conclusions and interpretations.

In conclusion, the results of the model validation provide strong evidence for the accuracy and reliability of the finite element models developed in this study. These models can be used with confidence for the design and analysis of long cylindrical concrete thin shells, and provide a valuable tool for further research and practical applications in this field.

6.3 Results

In this paper, a parametric study was conducted to anticipate the static behaviour of a concrete cylindrical shell. In order to achieve the aim of the study, two models were studied: The first model has a varying semi-central angle and constant thickness. Under the first model, three spans were considered: Type-A with span length of 10 m, Type-A' with span length of 20 m, and Type-A" with span length of 30 m. From the first model, the influence of the semi-central angle was studied. On the other hand, the second model has varied thickness and a constant semi-central angle. Under the second model, three spans were considered: Type-B with span length of 10 m, Type-B' with span length of 20 m, and Type-B" with span length of 30 m.

The finite element analysis was carried out by ANSYS software, and it shows that the maximum vertical deflection occurs in the mid span as indicated in blue colour zone, as shown in Figure 3. The maximum compressive stresses occur near the supports, as shown in Figure 4. The maximum tensile stresses occur in the mid span as indicated in the red colour in Figure 2.

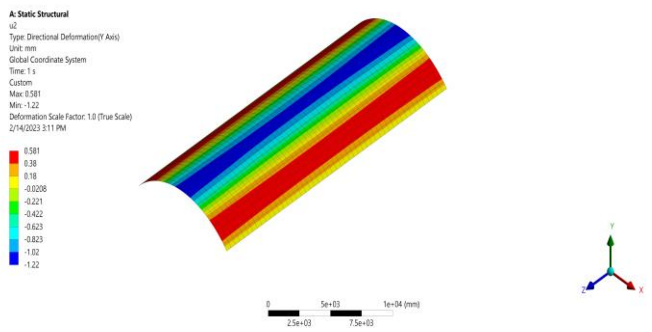


Figure 3. Vertical deflection diagram

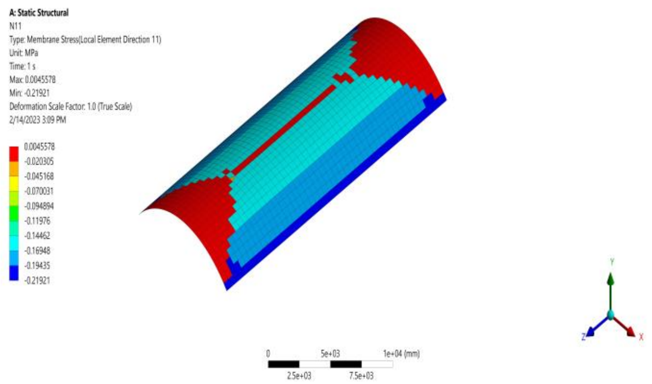


Figure 4. Membrane stress diagram

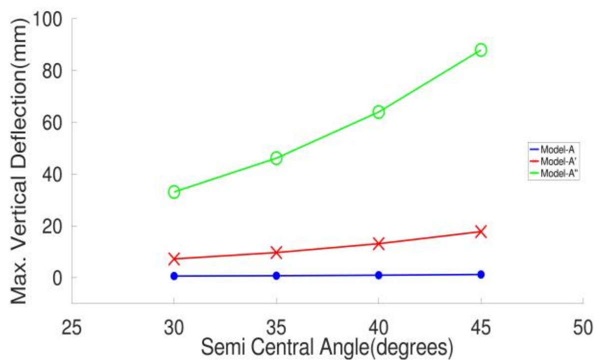


Figure 5. Max. vertical deflection for Type A, Type A' and Type A"

6.3.1 Influence of semi central angle

The semi central angle is a critical factor that impacts the static behaviour of concrete thin shells. The semi central angle refers to the angle between the vertical axis of the shell and the tangent to the mid-surface of the shell at the edge. The semi central angle has been shown to significantly affect the vertical deflection, maximum compressive stress, and maximum tensile stress of the shell.

As the semi central angle is increased, the vertical deflection of the shell also increases, as illustrated in Figure 5. This increase is due to the increase in the curvature of the shell, which results in a greater load-carrying capacity and increased deflection.

However, the impact of the increased semi central angle on the maximum compressive and tensile stresses is different. The increase in semi central angle leads to a decrease in the maximum compressive stress, as shown in Figure 6. On the other hand, the increase in semi central angle leads to an increase in the maximum tensile stress, as illustrated in Figure 7. This is because the increase in semi central angle results in a greater curvature, causing an increase in the tensile forces and a decrease in the compressive forces.

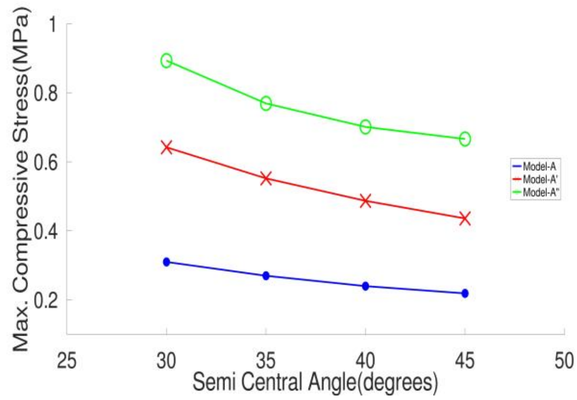


Figure 6. Max. compressive stress for Type A, Type A' and Type A"

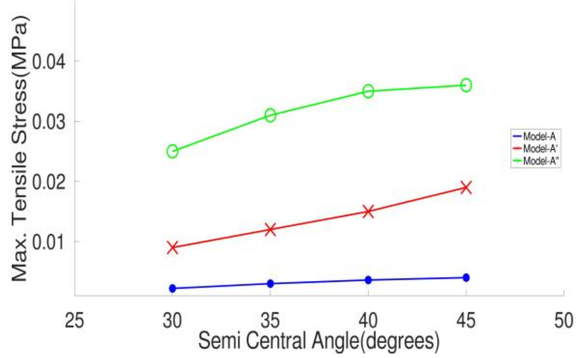


Figure 7. Max. tensile stress for Type A, Type A' and Type A"

6.3.2 Influence of thickness

The thickness of a concrete thin shell is a crucial factor in determining its static behaviour. As the thickness of the shell increases, there is a corresponding change in its vertical deflection, compressive stress, and tensile stress, especially if the semi central angle remains unchanged.

The influence of thickness on the vertical deflection of the shell is demonstrated in Figure 8. An increase in thickness leads to a decrease in vertical deflection, as long as the semi central angle remains unchanged. This decrease in deflection is due to the increased rigidity and strength of the shell, which allows it to better resist deformation.

In terms of the compressive and tensile stresses, the impact of thickness is less pronounced, as shown in Figures 9 and 10. If the semi central angle remains unchanged, an increase in thickness results in almost no change in the membrane compressive and tensile stresses. This is because the increased thickness results in a stronger and more rigid shell that has minimal impact on the stresses acting on the shell.

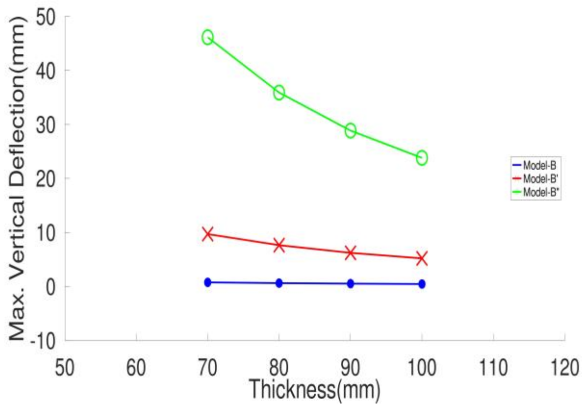


Figure 8. Max. vertical deflection for Type B, Type B' and Type B"

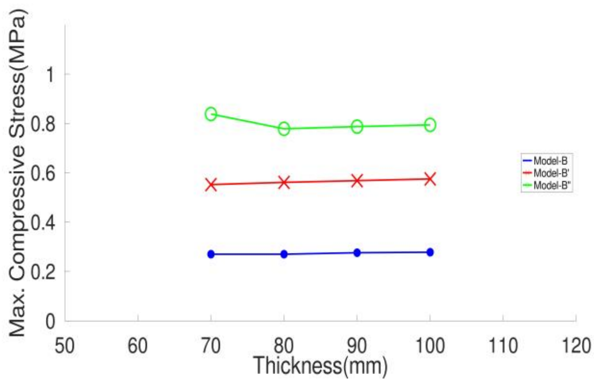


Figure 9. Max. compressive stress for Type A, Type A' and Type A"

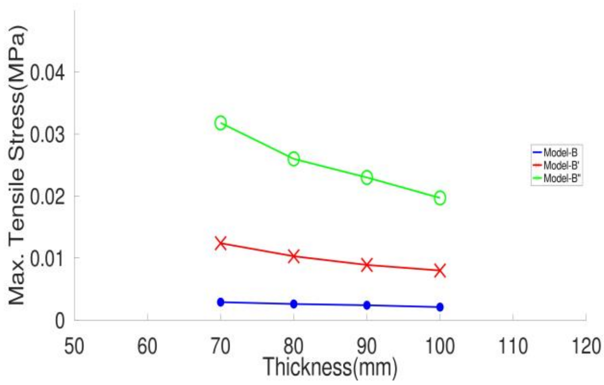


Figure 10. Max. compressive stress for Type A, Type A' and Type A"

7. CONCLUSIONS, SHORTCOMINGS AND FUTURE WORKS

7.1 Conclusion

The following conclusions are drawn from the study of circular cylindrical concrete thin shell structures with different parameters:

(1) The semi central angle plays a crucial role in determining the static behaviour of thin concrete shells. The increase in semi central angle leads to an increase in the vertical deflection and maximum tensile stress, as demonstrated in Figures 2 and 4, respectively, while it leads to a decrease in the maximum compressive stress, as shown in Figure 3.

(2) The thickness of a concrete thin shell is a significant factor that influences its static behaviour. An increase in thickness leads to a decrease in vertical deflection and minimal changes in compressive and tensile stresses, if the semi central angle remains unchanged.

7.2 Shortcomings

Some of the major limitations of this research using finite element analysis includes:

(1) Inadequate consideration of material properties and their effect on the static behaviour of these structures, particularly with respect to aggregate size and shape.
(2) Insufficient attention to the role of geometric imperfections, such as out-of-roundness and deviations from ideal circular cross-sections, and how they impact static behaviour of these structures.
(3) Limited validation of finite element models with comprehensive experimental data, particularly for real-world applications.

7.3 Future works

It is recommended some future research opportunities in this area include:

(1) Improving the accuracy of finite element models by incorporating advanced material models and better capturing the influence of geometric imperfections.
(2) Validation of finite element models through extensive experimental testing programs and comparison with real-world data.
(3) Investigating the use of new materials and construction techniques, such as fiber-reinforced concrete or the integration of smart materials and sensors, to improve the performance of these structures.
(4) Developing updated design guidelines and codes of practice that reflect the most current knowledge and best practices in the field of long cylindrical concrete thin shell structures.

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NOMENCLATURE

FE	finite element
L	shell length, m
S	shell span, m
R	radius of curvature, m
T	shell thickness, m
E	elastic modulus, MPa

Greek symbols

ν	Poisson ratio