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Original Research Article

Stability and Dynamic Response of Thin Concrete Cylindrical Shell Columns: Influence of Reinforcement and Geometric Parameters

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Abstract

Thin reinforced concrete cylindrical shells, commonly used in silos, storage tanks, and offshore platform legs, combine high strength-to-weight ratios with efficient load-bearing capacity. Their slender geometry, however, makes them highly susceptible to buckling, and existing studies on metallic or composite shells inadequately capture the behavior of concrete shells with embedded steel. This study presents a numerical investigation of thin reinforced concrete cylindrical columns under axial compression, focusing on the influence of reinforcement details and column geometry on critical buckling loads. Finite element simulations and parametric eigenvalue analyses were performed using Abaqus to identify buckling modes and evaluate stability. Results show that increasing the longitudinal bar diameter from 10 mm to 16 mm raised the first-mode buckling load from 9.420×10^7 N to 9.524×10^7 N, while increasing the number of bars from 8 to 12 increased the load from 9.394×10^7 N to 9.463×10^7 N. Column length had the most significant impact: extending from 750 mm to 1000 mm reduced the first-mode load from 9.463×10^7 N to 6.195×10^7 N. Eigenvalue analysis revealed classical global buckling modes, with the first mode governing instability. The findings indicate that larger reinforcement and higher bar quantity enhance buckling resistance, with diameter improving axial rigidity and bar number improving circumferential stiffness distribution. Nevertheless, geometric slenderness dominates structural stability, underscoring that reinforcement optimization alone cannot fully counteract buckling risk. These results provide critical guidance for designing thin concrete shells, highlighting the importance of simultaneous control of geometry and reinforcement detailing to prevent structural failure.

Keywords: Thin Concrete Cylindrical, Shell Columns, Structure, Influence Reinforcement, Eigenvalue, Buckling Theory.

INTRODUCTION

Thin cylindrical shell structures are ubiquitous in engineering due to their high strength-to-weight ratio, structural efficiency, and ability to carry compressive and dynamic loads with minimal material consumption. In civil and offshore engineering, concrete cylindrical shells are used for silos, columns, storage tanks, and offshore platform legs where both stability and dynamic load resistance are critical design considerations. These structures operate under axial compressive loads, and their performance is dominated not just by material strength, but by geometric stability against buckling and dynamic responses under service and extreme loads.

One of the fundamental challenges in the design of thin shell columns is their susceptibility to instability phenomena, especially buckling. Thin shells are inherently sensitive to geometric imperfections and loading conditions, which can significantly reduce their critical load capacity compared to theoretical, ideally perfect configurations. Classical buckling theory, which assumes perfect geometry and loading, often overestimates the critical load; real structures exhibit complex instability patterns influenced by shell geometry, material inhomogeneity, and reinforcement details. Recent studies have reaffirmed that parameters such as thickness, slenderness ratio, and initial imperfections have profound effects on buckling behaviour, and comprehensive modelling must consider these factors for reliable structural assessment (Maharditya *et al.,* 2025).

Reinforcement is a critical design variable in reinforced concrete shells. While traditional research on cylindrical shells largely focuses on metallic or composite materials, there is growing interest in reinforced concrete applications structures where the interplay between concrete's compressive strength and steel's tensile properties governs overall stability. Research on vertical stiffeners and ribs in thin metallic shells shows that strategically placed reinforcement can enhance buckling resistance by up to 40%, highlighting the importance of reinforcement configuration in controlling instability (Cáceres *et al.,* 2025). However, despite this documented effect in metallic shells, investigations specific to reinforced concrete cylindrical shells under axial compression remain limited. Compared to steel shells, concrete shells combine nonlinear material behavior (cracking, crushing) with reinforcement mechanics, making their stability response more complex.

Most of the literature on cylindrical shell stability emphasizes the effects of geometric imperfections, boundary conditions, and external pressures, often for metallic or composite shells. For example, recent finite element studies demonstrate that geometric imperfections can substantially lower critical buckling loads, underscoring the need to include realistic imperfections in analyses (Veres, & Tănase, 2025). Additionally, parametric studies on composite-strengthened shells have shown that circumferential reinforcement layouts significantly delay buckling onset under external pressure, but such work generally pertains to external strengthening rather than integrated reinforcement in concrete shells (Taraghi *et al.,* 2021).

In reinforced concrete shell research, most studies have concentrated on flexural behaviour, axial capacity under combined loads, or concrete-filled steel tube columns. For instance, investigations into concrete-filled steel tubular (CFST) columns strengthened with FRP composites emphasize axial compressive performance and ductility, but do not directly address buckling phenomena specific to thin concrete shells (Mansour *et al.,* 2024). Similarly, experimental studies on double curvature buckling in circular reinforced concrete columns highlight the influence of reinforcement ratio on ultimate capacity and energy absorption, but do not provide systematic insights into shell buckling under slender geometries (Hamoda *et al.,* 2024). This indicates a notable research gap: while reinforcement effects on static strength and dynamic performance have been widely explored in general column research, there is a lack of systematic studies quantifying how reinforcement size, quantity, and distribution interact with geometric parameters to influence shell stability and dynamic response in reinforced concrete cylindrical columns.

Moreover, much of the classical shell stability literature focuses on metallic shells or theoretical imperfection sensitivity and does not adequately capture the composite behaviour of concrete and steel reinforcement under buckling and post-buckling conditions. The complex interaction between concrete damage, reinforcement yielding, and geometric slenderness in thin concrete shells necessitates targeted numerical investigation. Such studies are critical for advancing design methods beyond conservative code provisions, enabling safer and more material-efficient shell structures.

In the Nigerian and broader West African context, reinforced concrete cylindrical shells are frequently employed in water storage tanks, elevated tanks, columns in multistory buildings, and offshore structural legs. These applications face high axial loads and often dynamic effects from wind, seismic activity, or wave action, yet regional design practices rely heavily on simplified design charts that do not explicitly account for buckling instability influenced by reinforcement and geometry. This underscores the need for locally relevant research that bridges global analytical advances with regional structural practices.

The present study addresses existing gaps through a comprehensive numerical investigation of the stability and dynamic response of thin reinforced concrete cylindrical shell columns. It examines how variations in reinforcement characteristics, including bar diameter and quantity, as well as geometric parameters such as column length and slenderness, influence critical buckling loads and dynamic stiffness behaviour. Using advanced finite element modelling combined with parametric analysis, the study provides deeper insight into the interaction between reinforcement detailing and geometric effects on shell instability, with the aim of supporting more reliable and efficient design strategies for reinforced concrete shell columns under both static and dynamic loading conditions.

2. MATERIAL AND METHODS

2.1 Structural Idealization and Geometry

The structure investigated is a thin reinforced concrete cylindrical shell column subjected to axial compressive loading. The shell is characterized by radius (R), thickness h ($h/R \ll 1$) and length (L). The column is reinforced with uniformly distributed longitudinal steel bars embedded within the shell thickness.

A cylindrical coordinate system (r,θ,z) is adopted, where (z) denotes the axial direction. The shell is assumed isotropic and initially geometrically perfect. The design parameters considered is given in table 1.

Table 1: Material Constitutive Models: Design Parameter

Design Consideration	**Parameters (mm)**
Lenth Column	750 mm
External Column	300 mm
Internal Diameter	250 mm
Reinforcement Lenth	730 mm
Reinforcement Diameter	12 mm
Stirrup Diameter	8 mm
Number Rebar	12 mm
Concrete Grade	Grade 50
Parametric Study	
Reinforcement Diameter	Y_{10}, Y_{12}, Y_{16}
Number of Reinforcement	8, 10, 12
Length of Colum	750 mm, 1000 mm

2.2.1 Concrete Model

Concrete behaviour was simulated using the Concrete Damage Plasticity (CDP) model, which accounts for nonlinear compressive crushing and tensile cracking. The uniaxial stress–strain relationships are defined as:

$\sigma_c - (1 - d_c)E_c\varepsilon_c$ 1

$\sigma_t - (1 - d_t)E_c\varepsilon_t$ 2

Where E_c is the elastic modulus of concrete, d_c and d_t are compression and tension damage variables, respectively.

Plastic flow is governed by the Drucker–Prager–type yield function implemented in Abaqus, while stiffness degradation is controlled through damage evolution laws calibrated to concrete strength. The damaged plasticity model k_c implemented in the model ranges from 0.715 to 0.703, concrete elasticity modulus = 51000 MPa was assigned. Poisson ratio = 0.19 and the density of concrete implemented in the model is 2500 kg/m^3. The meshed concrete model is given in figure 1.

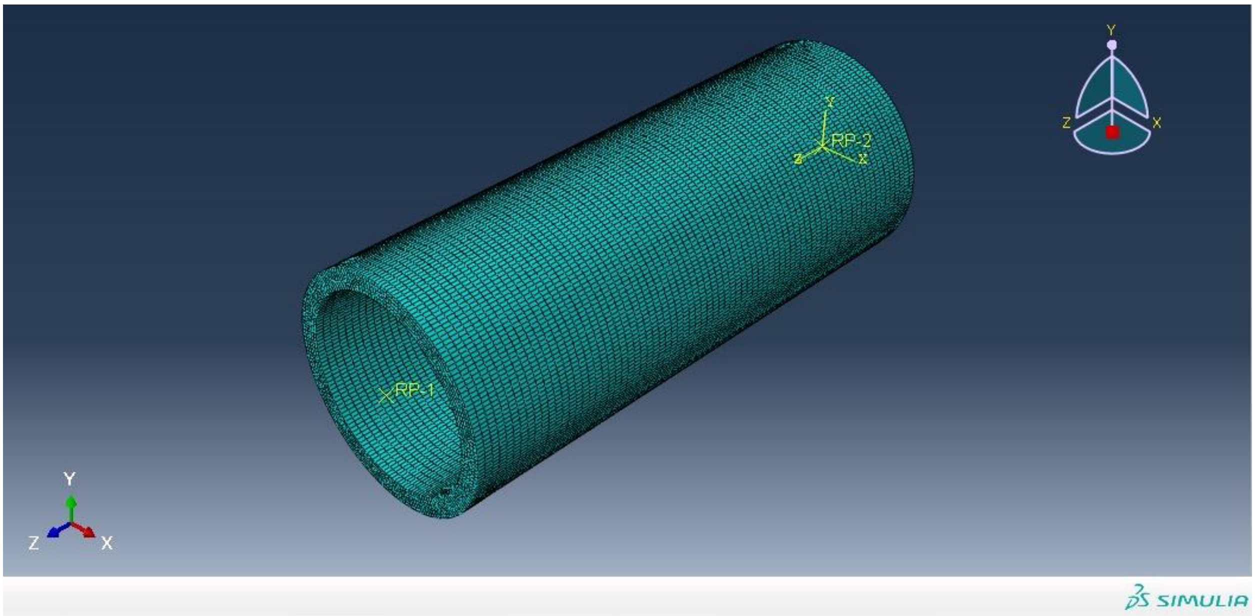


Figure 1: Meshed Concrete Shell Part

2.2.2 Steel Reinforcement Model

The steel reinforcement bars were idealized using an elastic–perfectly plastic constitutive model, characterized by linear elastic behaviour up to the yield point followed by plastic deformation at constant stress. The elastic modulus and yield strength defined the material response. A perfect bond between the steel reinforcement and surrounding concrete was assumed through embedded constraints, ensuring full strain compatibility and effective composite action throughout loading. The steel reinforcement was characterized by density of steel = 7850 kg/m^3, elasticity modulus = 200000 MPa, Poisson ratio = 0.3 and the reinforcement model is shown in figure 2.

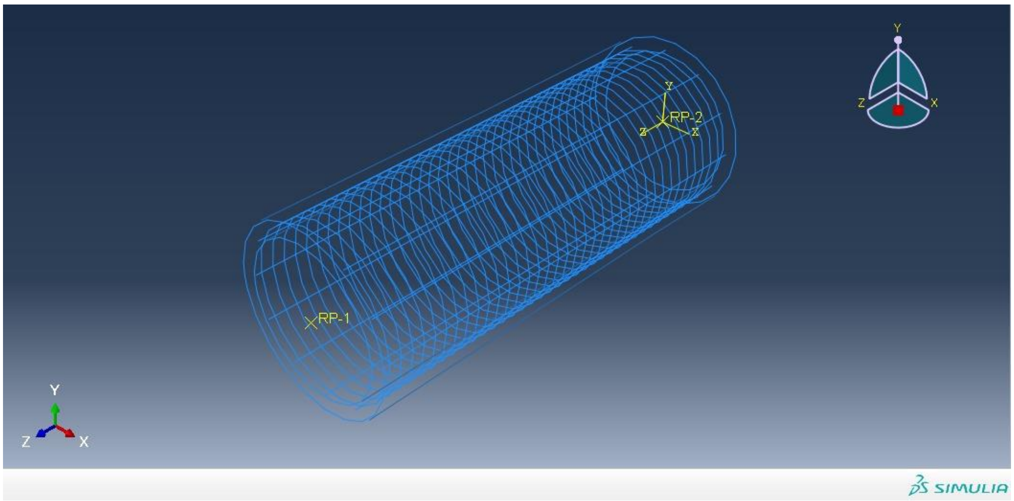


Figure 2: Wireframe View of Assembly Model

2.3 Shell Stability

The stability behaviour of the cylindrical shell column was formulated based on classical thin shell theory. Under axial compression, the shell response is governed by coupled equilibrium relationships linking radial displacement, flexural rigidity, and axial membrane forces. Linearized stability analysis was employed to capture elastic buckling behaviour, assuming small deformations and material linearity prior to instability.

Critical buckling loads were determined using an eigenvalue-based approach, in which structural instability occurs when the geometric stiffness induced by axial loading counterbalances the elastic stiffness of the shell. This formulation enables the identification of critical load levels and corresponding buckling modes governing the onset of instability.

2.4 Finite Element Modelling and Analysis Procedure

The shell was discretized using three-dimensional continuum elements, while reinforcement bars were modelled as embedded truss elements. Boundary conditions simulated a fixed base and restrained axial displacement at the top.

Three analysis stages were conducted:

1. Eigenvalue buckling analysis to determine critical loads and mode shapes
2. Nonlinear static analysis to capture post-buckling behaviour
3. Parametric analysis varying:
    - Reinforcement diameter (10, 12, 16 mm)
    - Number of reinforcement bars (8, 10, 12)
    - Column length (750 mm, 1000 mm)

3. RESULTS AND DISCUSSION

3.1 Buckling Mode Characteristics

Eigenvalue analysis revealed classical global shell buckling modes, characterized by axial half-waves coupled with circumferential undulations. The first mode governed structural instability for all configurations, while higher modes exhibited increased circumferential complexity but higher critical loads. The mode one linear buckle analysis output is given n figure 3.

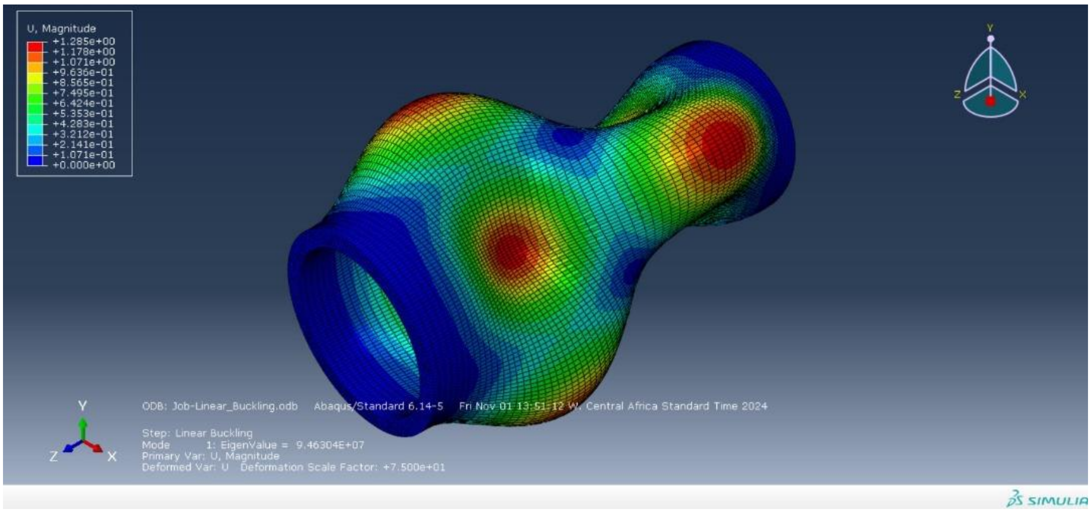
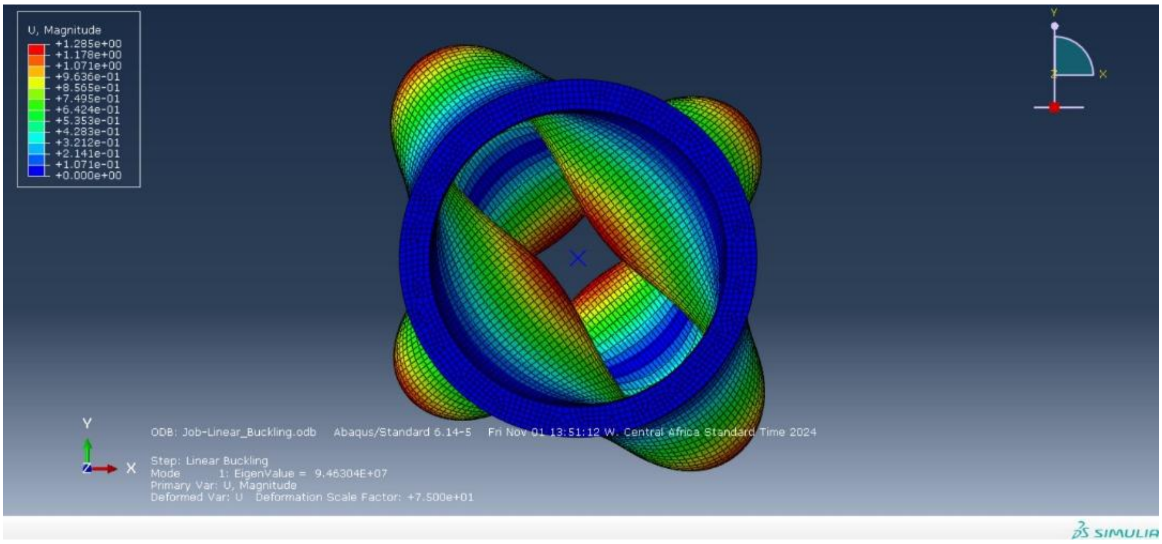


Figure 3: Mode One Linear Buckle Analysis Output (Lateral View)



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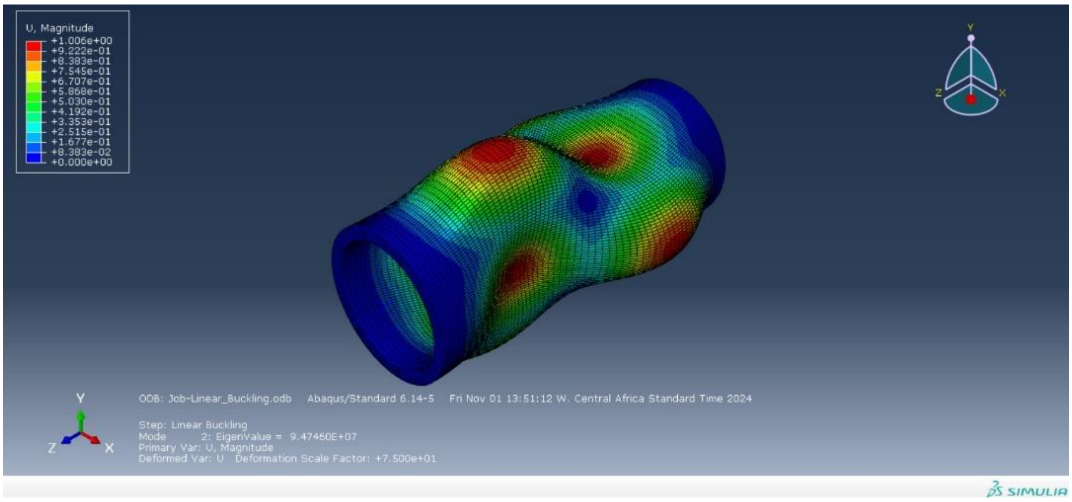
ODB: Job-Linear_Buckling.odb    Abaqus/Standard 6.14-5    Fri Nov 01 13:51:12 W. Central Africa Standard Time 2024

Step: Linear Buckling
Mode        1: EigenValue =  9.46304E+07
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +7.500e+01
```

Figure 4: Mode One Linear Buckle Analysis Output (Axial View)

The figures 4 and 5 shows the deflection and deformation pattern and eigenvalue (Buckle load) in the first mode of deformation of the shell column under linear buckling analysis implemented in the Abaqus software for both lateral and axial views.



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ODB: Job-Linear_Buckling.odb    Abaqus/Standard 6.14-5    Fri Nov 01 13:51:12 W. Central Africa Standard Time 2024

Step: Linear Buckling
Mode        2: EigenValue =  9.47460E+07
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +7.500e+01
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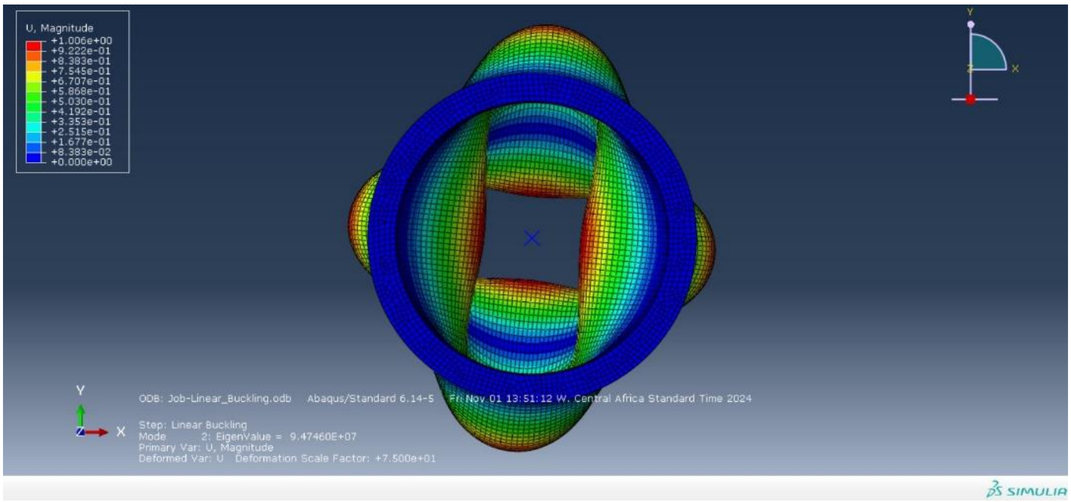
Figure 5: Mode Two Linear Buckle Analysis Output (lateral View)



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ODB: Job-Linear_Buckling.odb    Abaqus/Standard 6.14-5    Fri Nov 01 13:51:12 W. Central Africa Standard Time 2024

Step: Linear Buckling
Mode        2: EigenValue =  9.47460E+07
Primary Var: U, Magnitude
Deformed Var: U   Deformation Scale Factor: +7.500e+01
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Figure 6: Mode Two Linear Buckle Analysis Output (Axial View)

The figure 6 show the deflection and deformation pattern and eigenvalue (Buckle load) for the second mode of deformation of the shell column under linear buckling analysis implemented in the Abaqus software for both lateral and axial views.

3.2 Influence of Reinforcement Diameter on Buckling Load

The effect of reinforcement diameter on the buckling behaviour of the cylindrical shell column was evaluated by varying bar diameters while maintaining constant column length, number of reinforcement bars, and all other geometric and material properties. The eigenvalue buckling loads obtained for the first three modes are summarized in table 2, with corresponding graphical representation shown in figure 7.

Table 2: Buckling Loads of Column under Various Reinforcement Diameter

Mode	**Buckling Load × 10^7 [N]**		
Bar diameter	**10mm**	**12mm**	**16mm**
1	9.42004	9.46304	9.52439
2	9.42354	9.47460	9.54927
3	9.53997	9.55780	9.65229

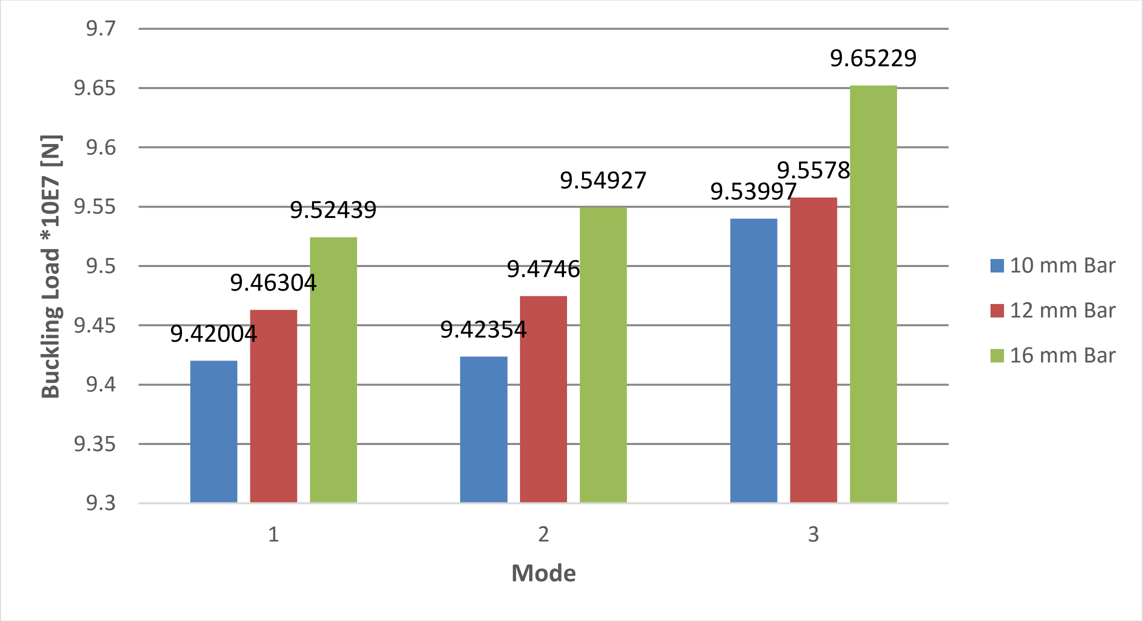

Figure 7: Effect of Reinforcement Diameter on Buckling Load

The results indicate a consistent and monotonic increase in critical buckling load with increasing reinforcement diameter across all three buckling modes. For the fundamental mode, the buckling load increased from 9.42004×10^7 N to 9.52439×10^7 N as the reinforcement diameter increased. Similar incremental trends were observed for the second and third modes, with higher modes consistently exhibiting larger critical loads.

This behaviour can be attributed to the increase in axial and flexural rigidity of the composite column section resulting from larger reinforcement diameters. As reinforcement size increases, the effective stiffness of the reinforced concrete shell improves, thereby enhancing its resistance to instability under axial compression. The increased steel contribution also improves stress redistribution within the shell, delaying the onset of buckling.

Although the observed increase in buckling load is gradual, the trend is systematic and confirms that reinforcement diameter is an effective parameter for improving shell stability, particularly in thin-walled columns where stiffness enhancement plays a critical role in delaying elastic instability.

3.3 Influence of Reinforcement Bar Number on Buckling Load

The influence of reinforcement quantity on buckling performance was examined by considering three reinforcement configurations consisting of 8, 10, and 12 longitudinal bars. The resulting eigenvalue buckling loads for the first three modes are presented in Table 3 and illustrated in Figure 8.

Table 3: Buckling Loads of Column under Various Reinforcement Diameter

Mode	**Buckling Load × 10^7 [N]**		
No of Reinforcement	**8**	**10**	**12**
1	9.39438	9.42672	9.46304
2	9.39998	9.43089	9.47460
3	9.51285	9.54933	9.55780

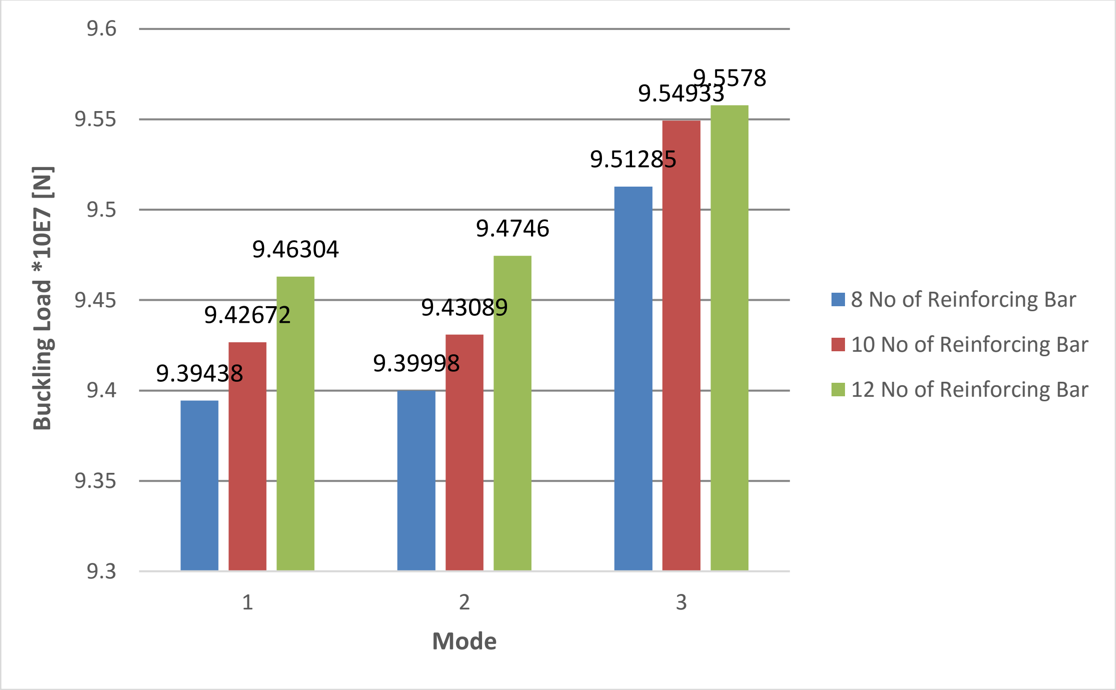

Figure 8: Effect of Reinforcement Bar Number on Buckling Load

The results demonstrate that increasing the number of reinforcement bars leads to a clear increase in critical buckling load across all buckling modes. For the first mode, the buckling load increased from 9.39438×10^7 N for 8 bar to 9.46304×107 N for 12 bars. Similar improvements were observed in the second and third modes.

The improvement in buckling capacity with increased reinforcement quantity is primarily due to the enhanced effective stiffness and improved circumferential stiffness distribution of the shell section. A higher number of reinforcement bars provides more uniform stiffness around the shell circumference, reducing localized deformation and stress concentration that may trigger premature instability. This uniformity becomes increasingly important for thin cylindrical shells, which are highly sensitive to stiffness irregularities.

The results further indicate that while both reinforcement diameter and quantity positively influence buckling resistance, reinforcement number contributes to stability by improving stiffness distribution, whereas diameter primarily enhances axial rigidity. This distinction highlights the importance of considering both parameters simultaneously in the optimal design of reinforced concrete cylindrical shell columns. Increasing the number of reinforcement bars led to notable enhancement in buckling resistance. Columns reinforced with 12 bars consistently outperformed those with 8 or 10 bars.

From a mechanical standpoint, increasing reinforcement quantity improves circumferential stiffness uniformity, reducing stress localization and delaying shell bifurcation. This effect is particularly significant in thin shells where instability is sensitive to stiffness distribution.

3.4 Influence of Column Length

The effect of column length on the buckling behaviour of the reinforced concrete cylindrical shell column was investigated by considering two lengths, 750 mm and 1000 mm, while all material properties, reinforcement configuration, and geometric parameters were held constant. The eigenvalue buckling loads obtained for the first three buckling modes are summarized in Table 4 and illustrated in Figure 9.

Table 3: Buckling Loads of Column Under Varying Column Length

Mode	Buckling Load × 10^7 [N]	
Length	750 [mm]	1000 [mm]
1	9.46304	6.19454
2	9.47460	6.27547
3	9.55780	6.35924

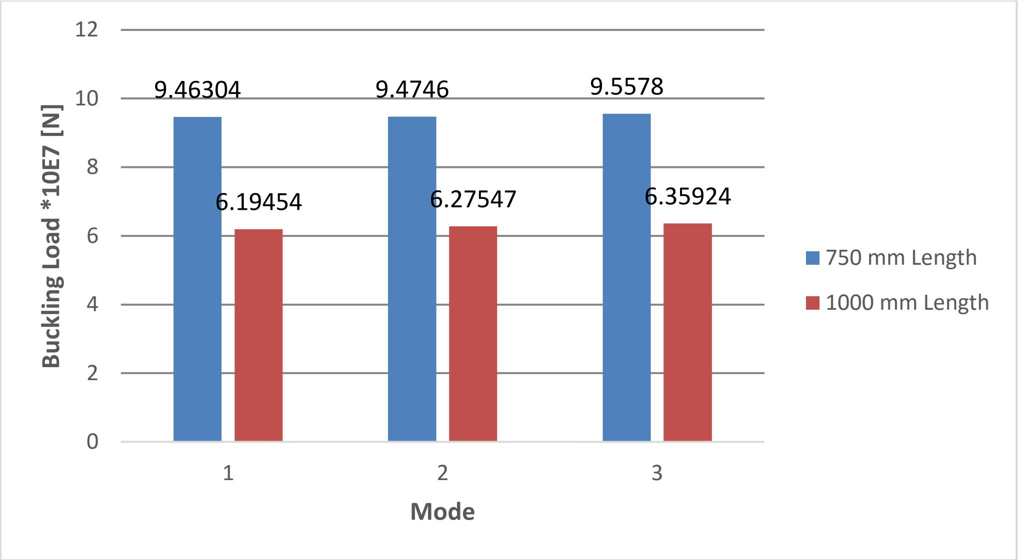

Figure 9: Effect of Column Length on Buckling Load

The results reveal a pronounced reduction in critical buckling load with increasing column length across all examined modes**.** For the fundamental buckling mode, increasing the column length from 750 mm to 1000 mm resulted in a reduction in buckling load from 9.46304×10^7 N to 6.19454×10^7 N, corresponding to a substantial decrease in load-carrying capacity. Similar reductions were observed in the second and third modes, confirming the dominant influence of column length on shell stability.

This behaviour is consistent with classical stability theory, which predicts an inverse relationship between critical buckling load and column slenderness. As column length increases, the slenderness ratio rises, leading to a reduction in axial stiffness and an increased susceptibility to global instability. In thin cylindrical shell columns, this effect is further amplified due to the coupling between axial deformation and radial shell buckling modes.

The magnitude of the observed reduction indicates that geometric slenderness is a governing parameter in the buckling response of reinforced concrete shell columns**,** often outweighing the stabilizing effects of reinforcement enhancement. While reinforcement diameter and quantity contribute positively to buckling resistance by increasing effective stiffness, their influence becomes secondary when column length increases beyond a critical threshold.

The enhancement of buckling resistance observed with increasing reinforcement diameter and reinforcement quantity in this study is consistent with trends reported in numerical and experimental investigations of stiffened and reinforced cylindrical shell systems. For instance, Zhang *et al.,*(2022) showed that longitudinal stiffening in thin cylindrical shells subjected to axial compression leads to noticeable increases in critical buckling load due to improved axial rigidity and suppression of localized deformation patterns. Similarly, Teng and Rotter (2020) reported that increased reinforcement content in cylindrical shell structures enhances load redistribution capacity and delays the onset of global instability, particularly in slender shells.

Studies focusing on externally reinforced or composite-enhanced shells also report comparable findings. Han *et al.,* (2021) demonstrated that increasing the stiffness contribution of reinforcing layers in cylindrical shells subjected to compressive loading resulted in higher critical loads and more stable post-buckling responses. Although their work concentrated on composite materials, the underlying mechanism stiffness enhancement leading to improved buckling resistance aligns with the behaviour observed in the present reinforced concrete shell columns.

The pronounced reduction in buckling load with increasing column length identified in this study strongly agrees with both classical shell theory and recent numerical analyses of slender shell structures. Liang *et* *al.,* (2023) emphasized that shell slenderness is a dominant factor governing global buckling, often exerting a greater influence on stability than material strength or reinforcement detailing. Likewise, Song and Teng (2021) demonstrated through finite element simulations that increasing the length-to-radius ratio significantly lowers the elastic buckling capacity of cylindrical shells, even when stiffness-enhancing measures are introduced.

The present results extend these findings by confirming that the dominance of geometric slenderness persists in reinforced concrete cylindrical shell columns, despite the beneficial effects of reinforcement. This observation reinforces conclusions drawn by Yu *et al.,* (2022), who noted that while reinforcement improves stiffness and delays instability, it cannot fully counteract the destabilizing influence of excessive shell length. In contrast to conventional reinforced concrete column studies such as those examining solid circular columns or concrete-filled tubular members the current investigation explicitly addresses shell-type instability. Previous studies on reinforced concrete columns under axial or cyclic loading (e.g., Liu *et al.,* 2021) primarily focused on strength, ductility, and energy dissipation rather than buckling phenomena. Thin cylindrical shell columns differ fundamentally in that instability arises from coupled axial–radial deformation modes, making them significantly more sensitive to geometric parameters than to material strength alone. The present study therefore provides complementary insight by highlighting stability mechanisms unique to shell columns, which are not adequately captured by traditional column models.

The numerical analysis shows that increasing reinforcement diameter and the number of longitudinal bars leads to consistent, though gradual, increases in critical buckling load across all examined modes. This confirms that reinforcement enhances shell stability by improving the effective axial and flexural stiffness of the composite section, primarily delaying the onset of buckling rather than altering the fundamental instability mechanism. In contrast, column length exerts a dominant influence on buckling behaviour. Increasing the length from 750 mm to 1000 mm caused a substantial reduction in critical buckling load, far exceeding the gains achieved through reinforcement enhancement. This highlights geometric slenderness as the controlling factor in the global instability of thin shell columns, with reinforcement unable to fully counteract adverse geometric effects. The study is limited by assumptions of geometric perfection, the exclusion of dynamic and time-dependent effects, and the absence of experimental validation. Nevertheless, the findings provide important design insights, emphasizing that effective stability design of thin reinforced concrete cylindrical shell columns must prioritize geometric control, particularly length and slenderness, alongside optimized reinforcement detailing.

4. CONCLUSIONS

This study presents a comprehensive numerical investigation into the stability and dynamic response of thin reinforced concrete cylindrical shell columns, with particular emphasis on the influence of reinforcement detailing and geometric parameters. The results demonstrate that increasing reinforcement diameter and the number of longitudinal bars consistently enhances the critical buckling load by improving the effective axial and flexural stiffness of the composite shell section, although the resulting gains are incremental. In contrast, column length was identified as the dominant parameter governing buckling behaviour, with increased slenderness leading to a pronounced reduction in critical load across all buckling modes. The key takeaway from this study is that while reinforcement optimization can delay the onset of instability, it cannot fully compensate for adverse geometric effects, and geometric slenderness remains the primary driver of global shell instability. The novelty of this work lies in its systematic evaluation of reinforcement and geometric influences within a thin reinforced concrete shell framework, extending shell buckling insights beyond the predominantly metallic and composite-focused literature. The findings have practical implications for the design of reinforced concrete shell columns used in tanks, silos, offshore structures, and load-bearing building elements, highlighting the need to prioritize geometric control alongside rational reinforcement detailing. Future applications of this work include extending the framework to imperfect geometries, dynamic loading conditions, and experimental validation to further enhance the reliability and applicability of shell stability design practices.

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