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Static Load Response of Laminated Composite Stiffened Cylindrical Shell Using Finite Element Analysis

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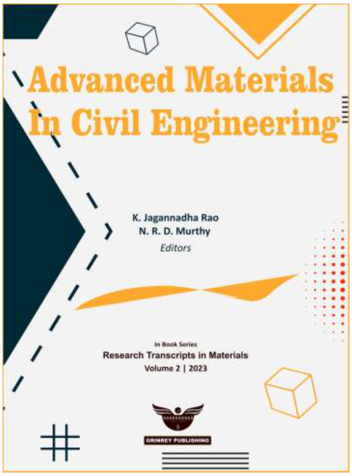

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Abstract

Laminated composites, a contemporary material, are widely used as a roofing option in civil engineering. They have benefits such as a lower weight-to-strength ratio, durability to harsh weather, and customizing options. However, researchers have expressed concern about the restricted transverse shear capacity, which can result in delamination under extreme strain, which is often confined inside the layers and eventually causes collapse. To overcome this, cylindrical shells are typically supplied with stiffeners to withstand static pressure deformation. There is a dearth of extensive research on the behaviour of laminated composite stiffened cylindrical shells under static loads in the existing literature. The purpose of the study is to investigate the behaviour of laminated composite stiffened cylindrical shells in terms of total deformation, maximum principal stress, and maximum principal strain caused by static pressure. On both simply supported and clamped two-ply laminated cylindrical shells, various stiffener sites are investigated. The stacking sequences are changed to compare the parameters mentioned. This study conducts a parametric investigation to draw engineering-relevant conclusions using ANSYS. According to the study's conclusion, the inclusion of differentially organized stiffeners results in a reduction in deformation, stress, and strain levels.

1. Introduction

Superior strength-to-weight ratio materials are needed for lightweight machine parts and lightweight constructions. Another aspect that cannot be ignored in contemporary practical application is durability. Integrating laminated composite materials in building is one of the effective answers to these strict standards. Laminated composite structural systems, however, are destroyed by matrix fissures, bonding flaws between distinct laminate and delamination, according to study studies from the last two decades. During the production or use of multilayer composites, laminae regularly delaminate or separate, which can even cause the structure to completely collapse. But eye inspection seldomly reveals the location and severity of such damage. According to Crawley [1], increasing aspect ratio leads bending mode to prevail and slight flexural coupling causes nodal pattern of mode geometries to be antisymmetric in laminates with angle plies. According to Shen and Grady [2] and Krawczuk et al. [6,7], natural frequency is most significantly affected by presence of structural failure at the mid-surface of laminate, and as distance in between delamination and mid-surface grows sensitivity usually decreases. Qatu and Leissa [3] provide effective vibration analyses for laminated composite twisted plate surface. Impact of several characteristics like material, layers, fibre angles, and curvature on natural frequencies are also examined by Qatu and Leissa [4]. Tenek et al. [5] stated delamination has a substantially greater impact on higher frequencies than it does on lower frequencies. Present cylindrical shell analysis employs an eight-noded iso-parametric curved quadratic shell element with five degrees of freedom. Earlier research published by Chakravorty [8] demonstrates methodical growth of stiffness matrix, ensuring compliance of displacement and equilibrium of generalized forces at delamination crack front. Delamination of composite characterization is therefore crucial. In this regard, delamination-related alters in modal frequencies provides hint for delamination identification as mentioned by Diaz [9]. Ghosh and Chakravorty [10] reported linear as well as nonlinear strains to interpret failure criterion of shell. Hee-Keun Cho [11] conducted research on optimization of laminated composite cylindrical shells to maximize the resistance to buckling and failure when subjected to axial and torsional loads. Bakshi [12] described a nonlinear finite element analysis for predicting failure loads on a laminated composite cylindrical shell panel. Thakur et al. [13] investigate the behaviour of layered shells using the C0 FEM based on HSDT. Dona et al. [14] provided design criteria for skewed laminated composite hypar shells with partially open borders, considering both material failure and serviceability. Bakshi [15] described the mode shapes and fundamental frequencies of laminated curved stiffened shells for various stiffener variables such as orientations, eccentricities, numbers, depth, and varied boundary conditions. Keshav et al. [16] proposed the critical load and failure of laminated stiffened cylindrical panels. Pinho et al. [17] investigated thin shells using nonlinear analysis. The post-critical behaviour of sandwich shells enclosed by elastic medium was explored by Chen et al. [18]. The governing equations were developed by merging Reddy's HSDT with simplified nonlinearity.

Thorough survey of literature reveals the fact that some papers on laminated composite cylindrical shell have been studied over the years for different boundary conditions and loading parameters to study the structural responses, but the civil engineering form of stiffened cylindrical shell as a roofing entity remained scanty. This study aims to conduct a mathematical formulation on laminated composite stiffened cylindrical shell with simply supported and clamped boundary conditions.

2. Numerical Example

Present numerical formulation is employed to solve the natural frequencies of twisted plates which structurally resemble cylindrical shell.

This validates the stiffness and mass matrix formulation of present code. The details of the benchmark problem are illustrated in Table 1.

Table 1. Natural frequencies ($\tilde{\omega}$) for three-layer twisted plates

Twist angle	**ϴ**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
ϴ = 15°	Qatu and Lessia [3]	1.00	0.93	0.74	0.53	0.35	0.27	0.26
	Current Formulation	0.98	0.92	0.77	0.51	0.33	0.28	0.26
ϴ = 30°	Qatu and Lessia [3]	0.96	0.89	0.72	0.52	0.34	0.26	0.24
	Current Formulation	0.95	0.87	0.71	0.53	0.33	0.25	0.23

Apart from the problem mentioned above, static pressure induced response of cylindrical shell is studied for different boundary conditions and laminations. The surface geometry of the shell is shown in Fig. 1

(i) Constrains: Simply Supported (SS) & Clamped (CC)
(ii) Lamination: CP [0°/90°]; AP [45°/-45°]
(iii) Shell geometry: a = b = 1.0 m, R = a/10, t= a/100
(iv) Stiffener geometry: d = a/50, tt= a/100
(v) Material details: E_{11} = 120 GPa, E_{22} = 7.9 GPa,
$G_{12,23,13}$ = 5.5 GPa, ν_{12} = 0.3, ρ = 1.58 x 10^{-5} N-sec^2/cm^4
(vi) Static load = 10 kN/m^2
(vii) Eight-noded iso-parametric curved quadratic element (10 mm) mesh with five degrees of freedom was adopted.

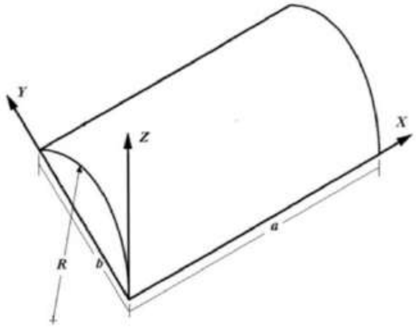


Fig. 1. Geometry of cylindrical shell

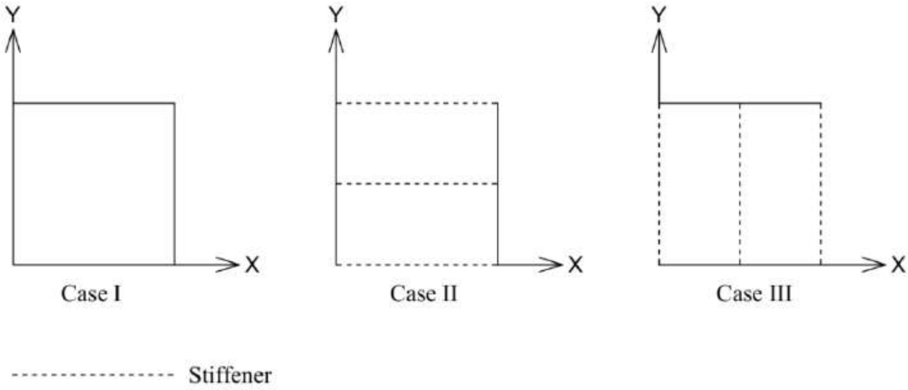


Fig. 2. Position of stiffeners

3. Result and Discussions

According to results obtained as shown in Table 1, Qatu and Lessia [3] reported frequencies and frequency response of twisted plates derived by current formulation are quite similar. This agreement verifies the stiffness and matrix formulation were correctly incorporated into the current code.

Table 2. and Fig. 3 to 5 represents all the results derived for cylindrical shell variable orientations and boundary conditions. Finite element mesh is automatically optimized by ANSYS. Mesh optimization was done considering the simpler and complex models and the final mesh was considered to be 10 mm. Furthermore, CP shells give lower value of deformation than AP shells for the same static pressure. The difference in deformation behavior between angle ply and cross ply shells can be attributed to the anisotropic nature of composite materials and the specific fiber orientations in each configuration: In an angle ply laminate, the fibers are oriented at an angle (+45º/-45º; in this study) to the primary load direction. This means that when a load is applied, the fibers are not directly aligned with the load direction. As a result, the fibers resist the load in a less efficient manner, leading to more deformation. The load applied to the laminate will induce both tensile and compressive stresses in the fibers, depending on their orientation. The presence of both tension and compression can lead to more complex stress distributions within the material, potentially causing more deformation compared to other

configurations. In a CP laminate, the fibers are oriented at right angles (0°/90°). This configuration is designed to maximize stiffness and strength in two orthogonal directions. When load is applied, the fibers aligned with the load direction (0°/90°) contribute more effectively to resisting the applied load, resulting in less deformation. The fibers perpendicular to the load direction help to counteract shear and provide stability to the laminate. It is clear from the figures that the maximum deformation is well restricted due to the presence of the stiffeners. Although, both the stiffener cases considerably diminish the value of maximum deformation, the longitudinal stiffener case provides larger resistance to deformation. The maximum deformation of SS shells is found to be greater than CC shells.

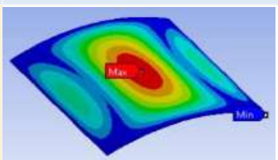
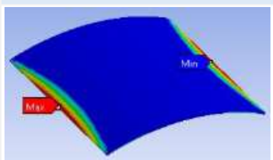
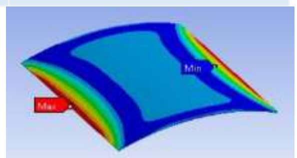
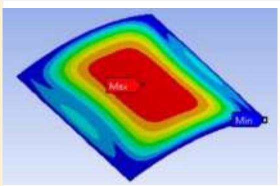
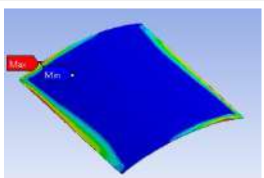
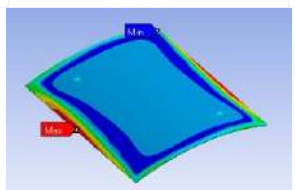
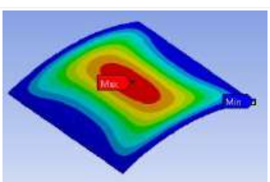
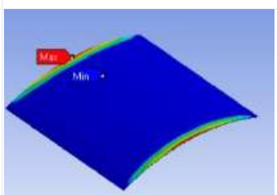
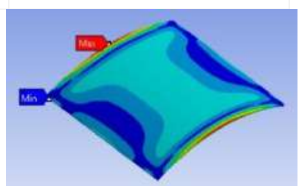
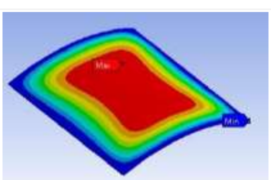
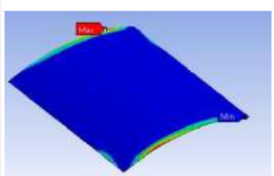
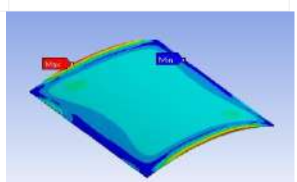
Boundary conditions	**Ply-orientation**	**Maximum deformation (mm)**	**Peak Principal Stress (MPa)**	**Peak Principal Strain**
SS	CP [0º/90º]			
	AP [45º/-45º]			
CC	CP [0º/90º]			
	AP [45º/-45º]			

Fig. 3. Peak deformation, principal stress and strain contours of Case I

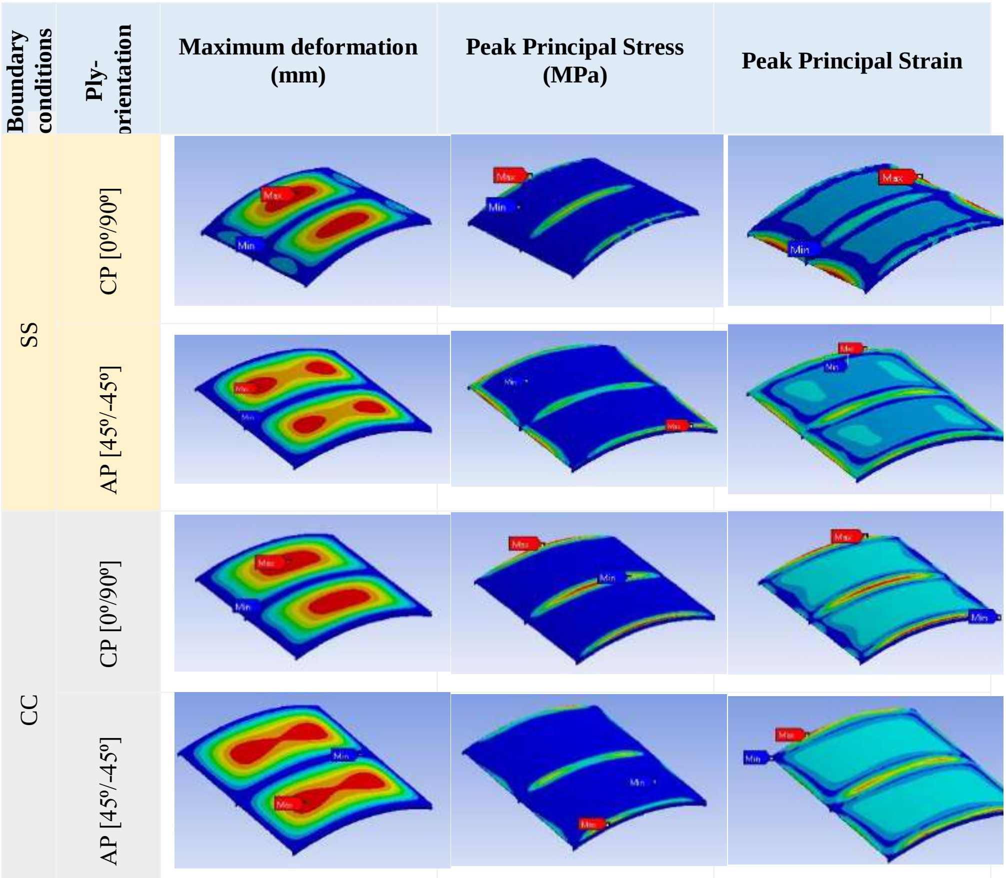


Fig. 4. Peak deformation, principal stress and strain contours of Case II

In a simply supported shell, the edges are allowed to move freely in the radial direction but are prevented from moving in the axial direction (along length of shell). This means the edges can rotate and move slightly, which can lead to larger deformations. The presence of radial movement and rotational freedom at the edges of a simply supported shell increases its overall flexibility. This flexibility allows the shell to accommodate larger deformations when subjected to external loads. In a simply supported configuration, the loads applied to the shell can lead to more complex stress distributions and load-sharing mechanisms. This can result in larger deformations as stress concentrations may occur at certain points. In a clamped (fully fixed) shell, the edges are completely constrained from any movement or rotation. This constraint restricts the shell's ability to deform, resulting in smaller deformations. Clamped shells, being fully fixed at their edges, are less flexible and have limited degrees of freedom for deformation. The constrained edges resist deformation more effectively. Clamped shells have a more uniform stress distribution due to the fixed edges. This can lead to more predictable and limited deformations. In summary, simply supported cylindrical shells can exhibit larger deformations compared to clamped shells due to their increased flexibility and the freedom of movement at their edges. Clamped shells, being fully constrained, generally have more limited deformation behavior. The deformation contours seem to be divided in by the presence of the stiffeners as shown in Figure 4 & 5.

While analyzing the stress generation it was witnessed that AP shells results in higher stress concentration than CP shells. The occurrence of higher stress in angle-plied (AP) shells compared to cross-plied (CP) shells can also be attributed to the structural arrangement of the shell layers. The difference in layer orientation directly affects the way stress is distributed within the shell under external loads. In angle-plied shells, the layers are aligned along certain directions that might not be optimally aligned with the primary load direction. This can result in stress concentrations in certain areas, leading to higher localized stresses. On the other hand, cross-plied shells distribute the stress more evenly across different orientations of layers, potentially mitigating the concentration of stress. Additionally, the orientation of layers in angle-plied shells can create situations where shear forces are not well absorbed by the layers, causing shear stresses to build up, further contributing to elevated stress levels. Furthermore, Clamped shells typically result in higher stress generation than simply supported shells due to the differences in their boundary conditions and the resulting constraints on their deformation behavior. When a shell is clamped, its edges are rigidly fixed in place, meaning they cannot move or deform. This creates a situation where the shell is restrained from expanding or contracting in response to applied loads. As a result, any external forces applied to the clamped shell are concentrated and transmitted directly into the shell material, leading to localized stress concentrations. This concentrated stress distribution can result in higher stress levels within the shell structure. In contrast, in a simply supported shell configuration, the edges of the shell are allowed to move vertically to accommodate deformations. This movement allows the shell to distribute the applied loads more evenly across its surface, which helps to prevent localized stress concentrations. As a result, the stress generation in a simply supported shell is generally more uniform and less concentrated compared to a clamped shell.

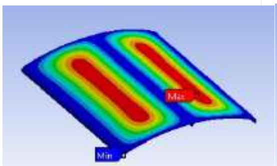
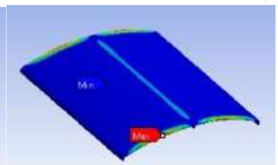
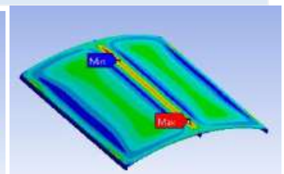
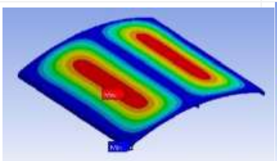
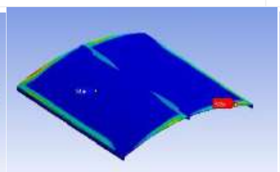
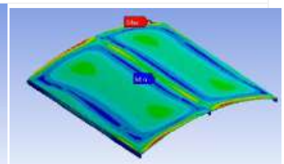
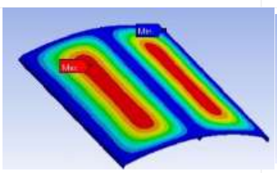
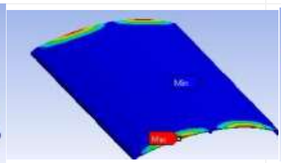
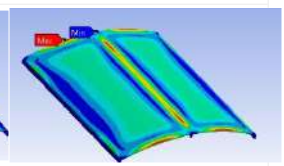
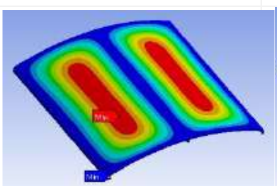
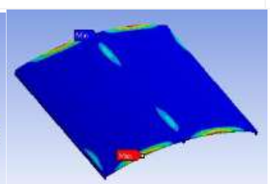
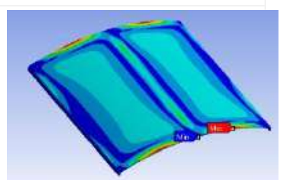
Boundary conditions	Ply-orientation	Maximum deformation (mm)	Peak Principal Stress (MPa)	Peak Principal Strain
SS	CP [0º/90º]			
	AP [45º/-45º]			
CC	CP [0º/90º]			
	AP [45º/-45º]			

Fig. 5. Peak deformation, principal stress and strain contours of Case III

Strain analysis showed similar results, as AP shells led to larger strain than CP shells. However, CC shells led to lower strain generation than SS shells. This can be attributed to the misalignment of layers in angle-plied shells relative to the applied loads which can lead to inefficient stress distribution and increased strain. Cross-plied shells, with their alternating layer arrangement, are better equipped to evenly distribute loads and manage deformation, resulting in lower strain values. Moreover, the fixed boundaries of clamped shells limit their deformation and contribute to lower strain generation by preventing the shell from undergoing significant shape changes. In contrast, simply supported shells can deform more freely, leading to higher strain values as they adjust to the applied loads.

Table 2. Maximum deformation, peak principal stress and strain for different boundary conditions and ply-orientations

Boundary condition	Case No.	Ply-orientation	Maximum Deformation (mm)	Peak Principal Stress (MPa)	Peak Principal Strain
SS	I	CP [0⁰/90⁰]	0.13452	1.5619	0.000086461
		AP [45⁰/-45⁰]	0.1579	4.4939	0.000088095
	II	CP [0⁰/90⁰]	0.056616	1.5031	0.000074895
		AP [45⁰/-45⁰]	0.07485	3.3351	0.000078545
	III	CP [0⁰/90⁰]	0.048552	1.4704	0.0000296
		AP [45⁰/-45⁰]	0.07123	3.0691	0.000044936
CC	I	CP [0⁰/90⁰]	0.061173	3.6577	0.000030304
		AP [45⁰/-45⁰]	0.074107	2.6426	0.000049922
	II	CP [0⁰/90⁰]	0.042383	3.503	0.000027916
		AP [45⁰/-45⁰]	0.064679	1.9089	0.000047053
	III	CP [0⁰/90⁰]	0.037429	2.6696	0.000020423
		AP [45⁰/-45⁰]	0.055889	1.7176	0.000045976

4. Conclusions

At the end of the numerical studies, the following conclusions are derived from present study.

- The accuracy of the method is established by the close agreement between the findings achieved using the current method and those found in the published literature.
- Cross-plied (CP) shells are characterized by a structural arrangement where layers of material are oriented at different angles to each other.

In comparison to angle-plied (AP) shells, which have layers aligned at a specific angle, CP shells demonstrate a tendency to undergo reduced deformation. This suggests that CP shells possess a higher level of structural rigidity and are less prone to distortion under applied forces or loads.

- When considering the behavior of shell structures, the clamped (CC) configuration refers to a condition where the edges of the shell are securely fixed in place. In contrast, the simply supported (SS) configuration implies that the edges are allowed to move freely in response to external loads. In this context, CC shells exhibit a characteristic of experiencing less deformation compared to SS shells. This can be attributed to the constraint imposed by the clamped edges, which restricts the shell's ability to bend or deform, resulting in a more stable and less flexible structure.
- The stress generation within shell structures can vary based on their design and configuration. In the case of angle-plied (AP) shells, it has been observed that they generate significantly higher levels of stress compared to cross-plied (CP) shells. This indicates that AP shells are more susceptible to internal forces that lead to stress accumulation. The distinct layer arrangement in AP shells likely contributes to this phenomenon, causing the material to experience greater stress concentrations under applied loads.
- Cross-plied (CP) and angle-plied (AP) shells differ in their response to strain, which is a measure of the deformation a material undergoes under load. CP shells exhibit slightly lower strain values when compared to AP shells. This suggests that CP shells are less prone to experiencing excessive deformation when subjected to external forces. The arrangement of layers in CP shells seems to distribute the strain more evenly, contributing to their ability to maintain their shape under load.
- The behavior of clamped (CC) shells and simply supported (SS) shells can be contrasted in terms of stress generation. CC shells tend to experience higher levels of stress generation when compared to SS shells. This could be attributed to the fixed edges of CC shells, which

restrict their ability to deform or deflect under load. As a result, the applied forces are more concentrated within the structure, leading to increased stress levels.

- In the context of strain, which measures the deformation of a material, clamped (CC) shells and simply supported (SS) shells exhibit different characteristics. CC shells demonstrate a tendency to yield lower strain values than SS shells. This is primarily due to the constraints imposed by the clamped edges of CC shells, which limit their ability to deform or bend. As a result, CC shells maintain their shape more effectively under load, leading to reduced strain compared to SS shells.
- The introduction of both circumferential and longitudinal stiffeners significantly reduces the extent of deformation induced by static pressure. Nevertheless, when comparing their effectiveness, the longitudinal stiffener proves to be more impactful in minimizing deformation.

Nomenclature

a,b	:	Length and breadth of shell in x and y directions
AP	:	Angle-ply
CC	:	Clamped
CP	:	Cross-ply
d	:	depth of stiffener
E_{11}, E_{22}	:	Elastic moduli
G_{12}, G_{23}, G_{13}	:	Shear moduli
R	:	Radius, height
SS	:	Simply-supported
t	:	Thickness of shell
tt	:	Thickness of stiffener
v_{12}	:	Poisson’s ratio
ρ	:	Density

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