Behaviour of Thin Cylindrical Shells Strengthened Using CFRP

Purnima S. Subash[1] Arunima Raj S[2]
[1]M tech Scholar [2]Assistant Professor
[1,2]Department of Civil Engineering
[1,2]Rajadhani Institute of Engineering and Technology, Nagaroor, Kerala, India

Abstract— Thin-walled cylindrical shell structures are extensively used in aerospace, nuclear, civil engineering, aircraft, storage vessels, industrial buildings and other fields due their efficient load carrying capacity. The purpose of this study is to investigate the behavior of the thin cylindrical shell strengthened by Carbon fiber reinforced polymer (CFRP). CFRP is a type of composite materials consists of carbon fiber and polymer. While the polymer serves as a cohesive matrix to preserve and hold the fibers together in structures, the carbon fibre adds strength and durability. Composite shells are widely applied in pressure vessels, reservoirs, and tanks, as well as in spacecraft and rocket parts and various infrastructure elements. CFRP composites were initially developed by aircraft and weapon industries. The use of CFRP composite materials has gained its popularity in the strengthening of different structures. The cylindrical shell specimens with composite cover and without composite cover subject to external pressure were investigated. The study focus on vibration characteristics and buckling behaviour of aluminium and steel cylindrical shells strengthened using the FEAST^{SMT}. FEAST^{SMT} software is the structural and heat transfer analysis software based on the finite element analysis (FEA) of structures developed by Vikram Sarabhai Space Centre (VSSC) and Indian Space Research Organization (ISRO). It is used to solve engineering problems with complicated geometries and different boundary conditions. The effects of fibre orientations, stress distribution, strain distribution and frequency variations on the strengthened thin cylinders are also investigated.

Keywords: Carbon Fibre Reinforced Polymers, Buckling, Vibration, Civil Engineering, Composite Shell, Thin-Walled Cylindrical Shell, Finite Element Analysis, FEAST^{SMT}

I. INTRODUCTION

Thin-walled cylindrical shell structures are extensively used in aerospace, nuclear, civil engineering, aircraft, storage vessels, industrial buildings, and other fields due to their efficient load-carrying capacity. The goal of this analysis is to analyze the buckling behavior of the cylindrical strengthened and unstrengthened by using Carbon fiber reinforced polymer (CFRP). CFRP is a type of composite consists of carbon fiber and polymer. The carbon fiber provides stability and immobility while the polymer acts as cohesive matrices to insure and held the fibers jointly in structures. Composite shells are widely used as pressure vessels, reservoirs and tanks, rocket parts, and in various components of the building. CFRP composites were initially developed by aircraft and weapon industries. The use of CFRP composite materials has gained popularity in the strengthening of different structures. Carbon fiber reinforced polymer (CFRP) strengthening of structures has been gaining increasing interest, traditionally applied to concrete structures, and more recently applied to steel structures. The cylindrical shell specimens with composite cover and without composite cover subject to external pressure were tested for finding the critical buckling load. Also, the study focuses on different fiber orientations on the composite shell specimen, which are used to check the most efficient lay-up for strengthening the thin-walled cylindrical shell structures.

This paper contributes in detail to the characteristics and the behavior of cylindrical shells unstrengthened and strengthened with externally attached CFRP composite subjected to external pressure. Thin-walled metal shell configurations are highly valuable in their use of material, but they are especially sensitive to lose by buckling. For various geometries and loading conditions, buckling can takes many different forms. This area of knowledge is particularly pertinent to a wide range of industries due to the complexity and importance in terms of its nature. Fiber-reinforced composite materials continue to experience increased adoption in aerospace, marine, automobile, and civil structures due to their high specific strength, high stiffness, and lightweight. A thin-walled cylindrical shell construction's extremely effective load carrying capacity comes with a propensity for buckling destabilization failure. Buckling analysis is a critical stage in the development of thin-walled structural components, for which buckling failure is one of the most common causes of failure because of their slenderness. Constructions from laminated composite shells are attracting particular interest because they have wide applications in the aircraft building, automobile industry, etc.

Carbon fiber reinforced polymer (CFRP) is an extremely strong and light fiber-reinforced that contains carbon fibers. However expensive to create, CFRPs are frequently used when high stiffness and a high strength-to-weight ratio are needed, such as superstructures of ships, automotive, aerospace, sports equipment, civil engineering, and an increasing number of consumer and technical applications.

Fig. 1: CFRP sheets

The properties of CFRP include Light lightweight strength to weight ratio, corrosion resistance, magnetic, Impervious to pests and woodpecker attack, material properties in different directions that can be tailored for a particular application, environmentally safe, and Low impact resistance. Because of their inherent lightweight, high strength, and high durability, the proliferation of FRP (fiberglass reinforced plastic) composite materials, which are

traditionally used in aerospace, shipbuilding, and automobile industries are gradually moving towards applications in newer areas such as the construction industry. In this paper, therefore, we develop an improved shell element with different fiber orientation suitable for strengthening of thin shell structures. It is believed that by presenting a study of strengthening the thin cylindrical shell and analyzing the buckling mode shapes and frequency distributions, a useful body of literature for understanding the stability of such structures will be made available for analysts and designers.
The main objectives of the present study are as following:

1) To study the buckling behaviour of unstrengthened and strengthened cylindrical shells using the FEAST software.
2) To study the free vibration characteristics of unstrengthened and strengthened cylindrical shells using the FEAST software and compare the results.
3) To compare the stress and strain distribution, deflection patterns and the frequency variations on cylindrical shells.

II. Analytical Programme

FEAST^{SMT} (Finite Element Analysis of Structures) is an analytical programme for structural and heat transmission analysis that has been developed using the finite element method by Vikram Sarabhai Space Centre / Indian Space Research Organization. The software was primarily developed for solving ISRO's launch vehicle and satellite structural engineering problems. PreWin is the graphical user interface-based pre /post-processor of FEAST. It provides state-of-the-art features for geometric modeling, mesh generation, model editing, and results in visualization. FEAST solver is seamlessly integrated with PreWin as a single application. With advanced solution algorithms, the solver can handle large order problems of structural engineering. FEAST-SMT is a completely new solver implemented using C++ with Object-oriented technology. The solution to the system's governing differential equations is obtained at discrete locations by FEAST-SMT solver by Sub-structured and Multi-Threaded (SMT) techniques. This has resulted in a considerable reduction of solution time, which is comparable with industry-standard software. The fundamental architecture of SMT can be easily extended to parallel processing of large order problems. PreWin, the GUI for FEAST is bestowed with the command line, menu-driven, and tree-based control/ model manipulation options. Models on the screen can be visualized in 3D, with rich rendering choices. Geometry representation in STEP and IGES format is supported in PreWin. PreWin is designed for intuitive interaction to reduce learning time and improved efficiency and features context-sensitive help. Hence, this software can be utilized not only in aerospace/ aeronautical engineering domains but also in other fields where structural and heat transfer problems need to be simulated.

III. Modeling

A. *Geometric modeling*

For the buckling and vibration analysis, a thin cylindrical shell specimen with dimensions as diameter (d), height (h), thickness (t) of 200, 800 and 0.45 mm are considered for the study. The boundary conditions selected for the thin cylindrical shell are fixed supported on bottom end and top end simply supported with a pressure load acting along z-axis are considered. The control specimen and strengthened specimens are modeled in steel and aluminium materials with same geometrical properties. For strengthened thin cylindrical specimen, CFRP were considered.

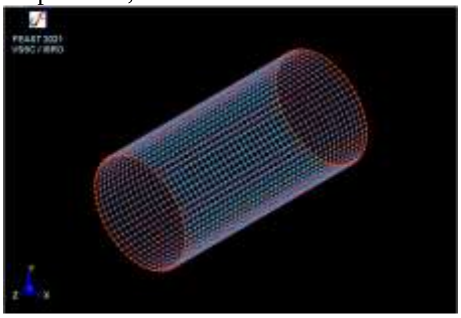

Fig. 2: FE model of steel cylindrical shell

The cylindrical shell made up of steel modelled using FEAST^{SMT} was shown in fig. 2.

B. *Material properties*

The material properties considered for the present analysis are, poison's ratio- 0.3, Modulus of elasticity -190,800 MPa and Stress- 205.480 MPa are the properties of the steel material selected for the study. Poisson's ratio- 0.3, Modulus of elasticity - 70 GPa are the properties of the steel material selected for the study. Young's Modulus, E_1= 240,000 MPa (longitude direction), E_2=E_3= 17,000 MPa (lateral direction). Poisson's Ratios, v_{12}=0.32, v_{23}= 0.45, v_{13}=0.32. Shear Modulus, G_{12}= 4500 MPa, G_{23}= 2500 MPa, G_{13}= 4500 MPa for orthotropic material.

IV. Results and Discussion

A. *Effect of stress and strain distribution on thin cylindrical shells*

The effects of stress and strain distribution on strengthened and unstrengthened thin cylindrical shells are obtained from the buckling analysis on both the shell and aluminium shells. From the results, it shows that the aluminium cylindrical shell strengthened with 1 layer of 0 degree fiber orientation has greater stress distribution than other fibre orientations and for minimum stress on aluminium cylindrical shell strengthened with 2 layers of 0 degree fibre orientations.

Material	Stress (x10^6 MPa)		Strain	
	Max.	Min.	Max.	Min.
Al	0.465	0.089	3.59	-6.45
Al + CFRP [0]	0.626	0.084	4.58	-8.69
Al + CFRP [0,0]	0.461	0.015	3.55	-6.34
Al + CFRP [0,0,0]	0.450	0.056	3.18	-6.341

Table 1: Stress And Strain Distribution on Aluminium Thin Cylindrical Shells

Similarly for cylindrical steel shells, strengthening with 3 layers of 0 degree fiber orientations has a greater stress than the other fiber orientations and for minimum stress on steel cylindrical shell strengthened with 2 layers of 0 degree fiber orientations.

Material	Stress (x10^6 MPa)		Strain	
	Max.	Min.	Max.	Min.

Steel	0.485	0.047	1.186	-2.41
Steel+ CFRP [0]	0.460	0.012	1.169	-2.07
Steel+ CFRP [0,0]	0.352	0.019	1.146	-2.06
Steel+ CFRP [0,0,0]	0.546	0.034	1.179	-2.90

Table 2: Stress And Strain Distribution on Steel Thin Cylindrical Shells

B. Effect of deflection and critical buckling load on thin cylindrical shell

The effect of deflection pattern and buckling load of both the aluminium and steel cylindrical shells are also obtained from the buckling analysis.

Material	Deflection (mm)	Critical load factor		Critical buckling load (N)
		Max.	Min.	
Al	1296.48	1.017	1.028	370.18
Al + CFRP [0]	1756.24	1.018	1.002	370.55
Al + CFRP [0,0]	1289.26	1.015	1.003	396.46
Al + CFRP [0,0,0]	1286.26	1.090	1.000	396.76
Al + CFRP [0,0,0,0]	1280.26	1.125	1.018	409.50

Table 3: Behaviour of Unstrengthened and Strengthened Cylindrical Shells (Aluminium)

Table 3 shows the behaviour of strengthened and unstrengthened aluminium cylindrical shells. From the table, it shows a minimum deflection of 1280.26mm for the aluminium cylindrical shell strengthened with 4 layers of 0 degrees fiber orientation of CFRP. The result also shows that the maximum critical buckling load for aluminium cylindrical shell strengthened with 4 layers of 0 degree fibre orientation.

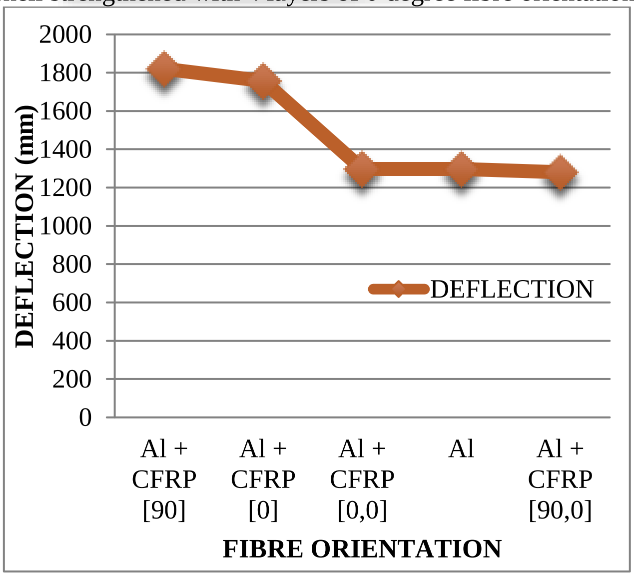

Fig. 3” Deflection v/s fiber orientation on unstrengthened and strengthened aluminium cylindrical shells

Material	Critical Load Factor		Deflection (mm)	Critical buckling load (N)
	Max.	Min.		
Steel	1.010	1.018	1453.72	367.64
Steel+ CFRP [0]	1.012	1.000	1585.65	368.36
Steel+ CFRP [0,0]	1.116	1.005	1324.69	406.22
Steel+ CFRP [0,0,0]	1.120	1.012	1315.64	407.68
Steel+ CFRP [0,0,0,0]	1.125	1.001	1275.39	409.5

Table 4: Behaviour of Unstrengthened and Strengthened Cylindrical Shells (Steel)

Table 4 shows the behaviour of strengthened and unstrengthened steel cylindrical shells. From the table, it shows a minimum deflection of 1275.396 mm for the steel cylindrical shell strengthened with 4 layers of 0 degrees fiber orientations. The result also shows that the maximum critical buckling load for steel cylindrical shell strengthened with 4 layers of 0 degree fibre orientation.

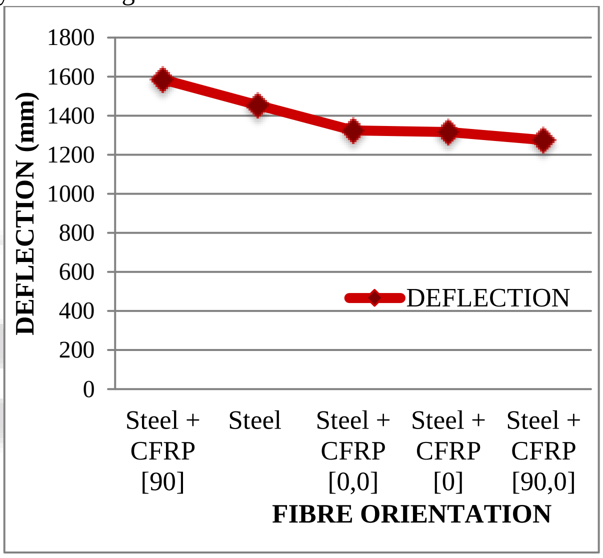

Fig. 4: Deflection v/s fiber orientation on unstrengthened and strengthened steel cylindrical shells

C. Effect of maximum and minimum frequency on thin cylindrical shells

The frequency variations are obtained from the free vibration analysis and the results shows the maximum and minimum frequency variations on different modes for both aluminium and steel thin cylindrical shells.

Material	Min. & max. Frequency (Hz)	
Al	174.85	256.46
Al + CFRP [0]	172.85	242.35
Al + CFRP [30]	172.85	251.08
Al + CFRP [45]	172.85	284.61
Al + CFRP [60]	172.85	245.71
Al + CFRP [90]	172.85	241.64

Table 5: Maximum and Minimum Frequency of Unstrengthened and Strengthened Aluminium Cylindrical Shells

Table 5 shows the maximum and minimum frequency of strengthened and unstrengthened aluminium cylindrical shells. From the table, it shows the maximum frequency of 284.612 Hz for aluminium cylindrical shell strengthened with 45 degree fibre orientation.

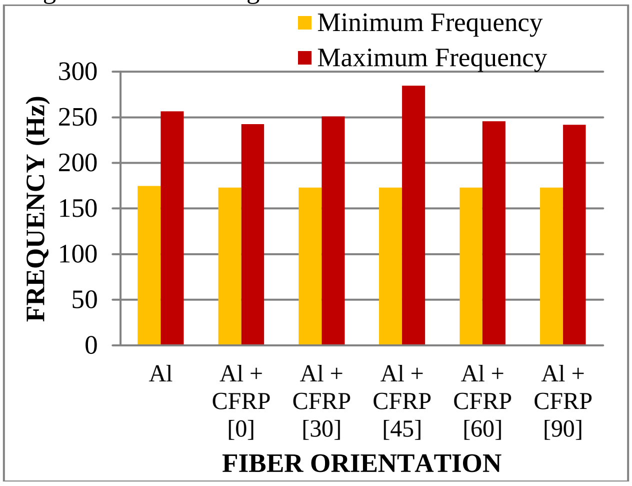

Fig. 5: Frequency v/s fiber orientation on unstrengthened and strengthened aluminium cylindrical shells

Material	Min. & max. Frequency (Hz)	
Steel	170.10	233.47
Steel + CFRP [0]	168.20	233.67
Steel + CFRP [30]	168.20	233.15
Steel + CFRP [45]	168.20	253.15
Steel + CFRP [60]	168.20	247.65
Steel + CFRP [90]	168.20	235.19

Table 6: Maximum and Minimum Frequency of Unstrengthened and Strengthened Steel Cylindrical Shells

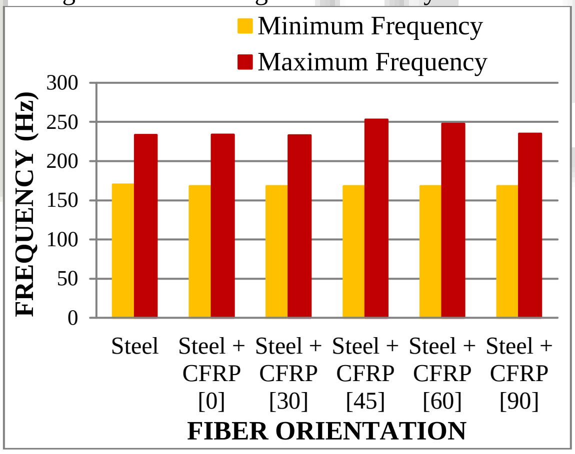

Fig. 6: Frequency v/s fiber orientation on unstrengthened and strengthened steel cylindrical shells

Table 6 shows the maximum and minimum frequency of strengthened and unstrengthened steel cylindrical shells. From the table, it shows the maximum frequency of 253.152 Hz for steel cylindrical shell strengthened with 45-degree fibre orientation.

V. CONCLUSION AND FUTURE SCOPE

Thin-walled cylindrical shell structures are often utilised in aerospace, nuclear, civil engineering, aircraft, storage vessels, industrial buildings, and other fields. Due to the extensive application of Shell cylindrical structure, the characteristics and behaviour of circular cylindrical shells have been a major topic of interest. So it is necessary to find a solution to strengthen the thin-walled cylindrical shell structures. In this investigation, an effort was taken to study the behaviour of unstrengthened and strengthened cylindrical shells using the FEAST software that have been utilized in different shell structures as strengthening, in order to find possible ways of utilizing these different fibre materials in huge strengthening practices for various structural applications.

After analyzing the analysis results, the following conclusions were drawn:

- The buckling strength was enhanced when CFRP composites were applied.
- The thin CFRP lamina increased the buckling strength of cylinder significantly.
- If the number of wraps is large, there will be a significant gain in buckling strength on thin cylindrical shells.
- The increase in buckling strength of thin cylindrical specimen depends on the change in thickness the CFRP.
- The aluminium and steel cylindrical shell strengthened with cross ply orientation of CFRP in 0 and 90 degrees shows a minimum deflection.
- The aluminium and steel cylindrical shell strengthened with 45 degree fibre orientation shows the maximum frequency.
- Fibre oriented in the circumferential direction provides a higher buckling strength.
- The lowest buckling strength was observed when the fibres were oriented vertically.
- The minimum frequency was observed when the fibre was oriented horizontally.
- The maximum frequency on strengthened thin cylindrical shell depends on the change in fibre orientation.
- i.e., Fibre orientation is an important factor which influences the behaviour of thin cylindrical shells.
- The bonding of CFRP to the exterior of a shell can be an economical repairing and strengthening technique.
- Several investigations were done in strengthening of thin cylindrical shells by various methods. Many studies are still going on in this field to improve the strength of thin cylindrical shells. In future, the work can be extended by bonding of CFRP to the exterior of an imperfect shell, even when only a relatively small zone was strengthened. By adopting this technique, we can also improve the structural properties of thin cylindrical shells. This method will be economical.

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