Defence Science Journal, Vol. 69, No. 4, July 2019, pp. 313-319, DOI : 10.14429/dsj.69.12634

Effect of Helical Winding Angle on External Pressure-based Buckling of Partially Filled Thin Composite Cylindrical Shells

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ABSTRACT

Effect of helical winding angle on buckling load of partially filled thin composite tubes is investigated in this work. Experiments are conducted on both empty and partially filled S2 glass tubes to estimate structural contribution of the filler material to improve buckling strength of shells. Chosen filler material mechanically simulates behaviour of typical solid propellant used in rockets for aerospace applications. FE analysis results with inclusion of non-linear effects correlates well with the experimental data. Three series of experiments are conducted to quantify the effect of helical winding angle and increase in volumetric loading fraction (VLF). Results confirm appreciable improvement in strength of filled tubes for higher VLF. For the chosen pattern of winding, lower winding angle provides more strength to the tubes against external pressure buckling.

Keywords: Winding angle dependency on shell buckling; Composite shell buckling with elastic fillers; External pressure buckling of composite shells

1. INTRODUCTION

Axisymmetric composite pressure vessels are generally fabricated using filament winding technique. These vessels are designed to withstand internal pressure for the intended purpose of their application. In an aerospace application typical examples of such vessel could be composite rocket motor casings. During their operational or deployment mode, these structures could be subjected to severe external pressure environment. The structure has to survive the external pressure load before it is utilised for its intended purpose of holding internal pressure. The rocket motor casings are filled with solid propellant which is a polymer based elastomeric material. This filler material adds certain strength to the composite casing which cannot be ignored. In case of a composite rocket motor casing, the winding angles are decided based on polar opening ratios and the choice of composite material. In the most of the cases this winding angle is decided to take care of internal pressure and winding feasibility on a given geometry. Buckling strength of the composite rocket motor casings is a strong function of this winding angle. This angle influences the effective stiffness of the casing. One needs to understand the behavioural dependence of these casings on the helical winding angle of the fibre used in fabrication of the structure. In addition, the inner filling with elastomeric material helps to improve the buckling strength further for the composite shell. In a composite rocket motor subjected to external pressure, the cylindrical shell portion of the casing takes most of the load. Contribution of either side end dome is not significant for withstanding external pressure load. Hence one can focus on the behaviour of the cylindrical shell to get an insight into the performance of CRMC under such a loading condition.

Herandez[1], *et al*. investigated the effect of winding pattern on external pressure capability of composite tubes. The authors experimented with glass-epoxy thin tubes, wound with 55^o helical angle but in a different rhomboid pattern. Implosion tests are conducted on tubes of various thicknesses. The research concludes that for a given winding angle, various winding patterns have no great influence on its external pressure based buckling strength.

Humberto[2], *et al*. conducted experimental research on buckling of T-700 (90°, 55°, 90°) carbon composite tubes. Non-linear behaviour study of composite under external load gives a good insight into the failure mode of both thin and thick tubes. Thin tubes fails in buckling where as thick tubes failure is predominant with shear failure leading to delamination.

Moon[3], *et al*. investigated the effect of helical winding angle on external pressure capability of composite tubes. Thin tubes with $\pm$ 30^o, $\pm$ 45^o and $\pm$ 60^o winding angles have been studied experimentally. Author reports that the major failure modes of the tubes predominantly depend upon the helical winding angle. Collapse of the tubes have been reported to be sudden and irrecoverable.

Rajamohan[4], *et al*. investigated behaviour of graphite epoxy composite shells. Both thick and thin shells are studied by the investigator. Two typical layup sequences such as $[0/90]_{9S}$ and $[\pm45]_{9S}$ are studied. Performance of shells with various R/t are reported. It is concluded by the author that winding

Received : 27 January 2018, Revised : 22 December 2018
Accepted : 19 February 2019, Online published : 15 July 2019

angle dependence is very strong for all R/t of shells. Typically for R/t of 100, the buckling load carrying capacity of shell with axial load condition is reported to be higher by ~ 40% for $[0/90]_{9S}$ layup sequence as compared to $[\pm 45]_{9S}$ layup.

Priyadarshini[5], *et al*. have reported the behaviour of empty composite cylinders under axial compression. A combination of various layup sequences, l/r, r/t and imperfection magnitude are investigated by the authors. The study indicates that irrespective of l/r ratios, buckling load carrying capacity of [0°, ±45°, 0°] cylinder is higher by 30 per cent as that of $[+45°]_2$ layup.

Mistry[6] investigated the optimum winding angle needed for E-glass cylindrical tubes. Author has studied winding angle from 10° to 85° for a combined load of external pressure and axial load. No hoop layup is considered in the work. Stress ratios up to 4:1 and 1:4 have been considered by the investigator. For an external pressure load stress ratio of 2:1, the author recommends an optimum winding angle of 81°. It is seen from the theoretical work that critical buckling pressure keeps monotonically increasing from a lower winding angle to higher ones. The author considers bifurcation load as well as first ply to failure approach in the research. Both the approaches indicate similar buckling strengths.

Messager[7], *et al*. carried out both theoretical and experimental investigations on carbon and glass composite tubes. The authors have done an optimisation exercise to report that an optimised winding of helical angle enhances the external pressure buckling strength by about 40 per cent as compared to traditional ± 55° winding. Investigators have conducted extensive experimental study on composite tubes of 400 mm length, 152.4 mm diameter and about 4mm thickness. Experimental results compare with theoretical data within an accuracy of 5 per cent . The theoretical buckling mode shapes reported in the study indicates one half wave longitudinally and 3 half waves in circumferential direction.

An earlier work of the present authors[8] has reported significant enhancement of buckling load carrying capacity for metallic thin shells in the presence of soft elastic filler material. Geometric imperfection modelling is also discussed in detail in the study.

Present study is a combination of experimental and theoretical investigations into the buckling behaviour of thin composite cylindrical tubes partially filled with elastic filler representing solid propellant used in present day composite rocket motors. Initially failure pattern of an empty composite tube is studied to get the idea of deflected geometry during external pressure application. Magnitude of displacement at failure of an empty tube is extended to the filled tubes to arrive at the instance of similar type of failure. Parametric study of winding angle is undertaken for various volumetric loading fraction (VLF) of the tubes.

2. EXPERIMENTS

Thin shell composite tubes are fabricated using S2 glass tow preg epoxy resin. The tubes had a winding pattern of (90°, ± θ, 90°) with a nominal total thickness of 2 mm. Helical angle θ is taken as parametric variable to fabricate different sets of cylindrical tubes. The tubes are wound on a CNC winding machine using a metallic mandrel and tow preg. During the winding activity, adequate numbers of infrared lamps are placed near the mandrel to ensure that the temperature of the tow is maintained at 40 °C when it reaches the mandrel. The dimensional details of the realised composite tubes is shown in Fig. 1. Tubes have a nominal length of 450 mm, 150 mm diameter and thickness of 2 mm. Three such sets of composite tubes with different helical angles (±θ) such as 15°, 30°, 45° are fabricated for parametric study. They are referred as Series-1, Series-2, and Series-3 tubes respectively in this work.

A suitable 0.5 mm thickness nitrile based rubber is bonded internally to the tubes using vulcanisation technique. This is essential to enable proper bonding of elastic filler. Elastomeric fillers representing typical solid propellant, in terms of its mechanical property, used in a rocket motors is filled into these tubes for varying VLF. A total of 18 tubes from each series are fabricated for testing. Three tubes from each series are unfilled and others are filled to five different VLFs such as 0.2, 0.4, 0.6, 0.8, and 0.9. Typical filled tubes and definition of VLF are as shown in Fig. 2.

A tailor made test setup is configured to conduct external pressure test on the composite tubes. Figure 3 presents this setup in schematic form. The tube is assembled into a leak proof structural steel chamber. Two end plates hold the tube in

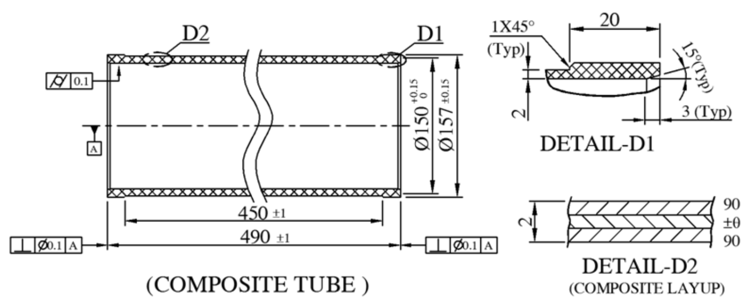

Figure 1. Dimensional details of realised composite tubes.

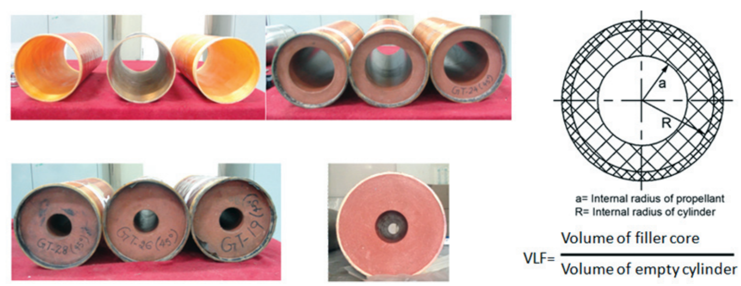

Figure 2. Typical photographs of empty and filled composite tubes.

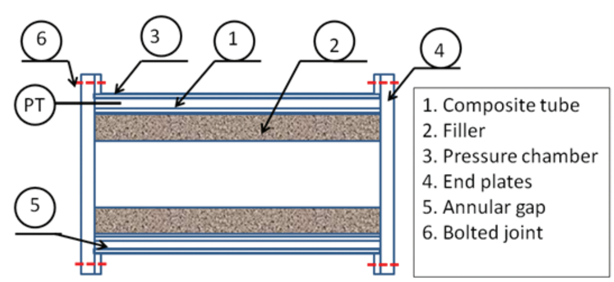

Figure 3. External pressure test set up for the composite tubes.

position without allowing axial and radial movement. Annular gap between the tube and chamber is pressurised using water. The annular gap pressure is measured using two digital pressure gauges. The pressure record is stored in a computer with a data rate of 100 Hz. Critical pressure (Pcr) for external pressure based buckling is noted from the peak magnitude of pressure time record.

At the outset empty shells are put for external pressure buckling tests. The objective of this test is to capture the pattern of failure and record the time history of deflection. It is important to know the absolute magnitude of radial deflection of the composite tube at the time of buckling. Secondly comparative study of experimental deflection pattern with increase in pressure against the theoretical prediction shall give a confidence to go for experiments with filled tubes. The test setup explained in Fig. 3 is used for the empty tubes with some additional instrumentation to measure real time radial deflection of empty tubes during the tests. Three laser based non-contact displacement transducers (NCDT) fitted to a bracket are placed at different axial locations inside the empty tube. Resolution of the sensors is capable of recording 10 μm displacement. Figure 4 presents empty tube hardware assembly fitted with the NCDTs. During the test, data of all the 3 sensors and two pressure transducers are recorded simultaneously in a computerised data acquisition system computer with a common time tag. The peak value of the annular gap pressure recorded for the test is considered as the buckling pressure or critical pressure for the respective composite tube. The behaviour of empty tubes under external pressure is well captured in this test. Three similar empty tubes are tested to note the spread of experimental data. The test data is stripped and compared with a non-linear FEM based analysis carried out with methodology reported later part of this work. The trend of both experimental and theoretical analysis shows a good match and is as shown in Fig. 5. Table 1 provides these numerical data. Mean critical pressure (Pcr) reported in three successive tests vary within 4.5 per cent of theoretically computed Pcr.

Figure 4. Photograph showing composite tube hardware assembly with NCDT: (a) NCDT on bracket, (b) Reflectors in tube, and (c) NCDT assembly with end plate.

Table 1. Critical pressure of empty Series-2 composite tubes

	Experiment	FE analysis
P_{Cr} (MPa)	0.595, 0.642, 0.717 (Mean = 0.651, Spread = 10%)	0.623

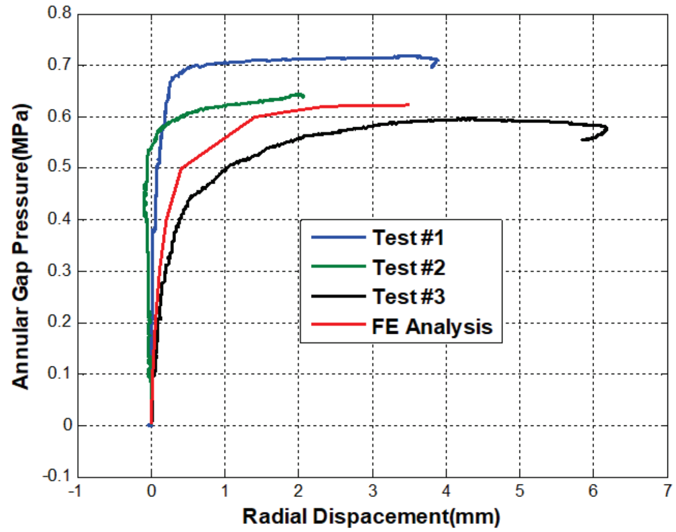

Figure 5. Comparative results of load-deflection of empty tube.

After studying the behaviour of three empty tubes, external pressure based buckling tests are conducted on partially filled tubes to quantify the effect of filling on buckling strength. More details of preparation and testing of tubes are reported in earlier research work of the Authors[9]. Displacement measurement on filled tubes is not possible due to practical limitation of space for mounting the sensors. However, since the empty and filled tubes are of similar dimensions, it is assumed that all tubes shall reach state of failure once absolute magnitude of radial deflection reaches to a maximum magnitude of 4 mm. In case of filled tubes, measurements are limited to two channels of annular gap pressure which ultimately records the Pcr. The experimental critical pressure obtained for all the three series of composite tubes are presented in Tables 2, 3 and 4, respectively for Series-1, 2 and 3 tubes. Three tests are conducted for tubes with a specific VLF. Mean value of each VLF series and data spread on each test are presented in these tables. Experimental data indicates a spread of about 10 per cent over average values. The mean value of critical pressure of each case shows that there is an incremental trend in load carrying capacity of the tubes as the VLF increases. As shown in the tables, significant gain in buckling load carrying capacity is observed for 90 per cent filled tubes in comparison to empty ones of respective series. It is seen that the composite tubes crack due to buckling but no specific shape is retained after the specimen is taken out of test chamber. Hence, no mode shape could be inferred from the test data. Probably a sophisticated optical real time 3D scanning technique can reveal mode shape related information.

3. FINITE ELEMENT ANALYSIS USING ANSYS SOFTWARE

Analytical study of the behaviour of both empty and partially filled composite tube is carried out using ANSYS software. Based on extensive physical measurement of dimensions of 45 composite tubes an imperfection magnitude of 0.2 mm on diameter is considered for the analysis. Engineering properties of S2 glass is obtained using flat laminate level

Table 2. Critical pressure for series-1(90°, ±15°, 90° winding) partially filled tubes

Test specimen	Ratio of radius (a/R)	Volumetric loading fraction (VLF)	Experimental critical pressure (Mpa)		
			All	Mean	% Variation over mean
1 2 3	1	0	0.623 0.642 0.691	0.652	+5.9 -4.6
4 5 6	0.89	0.2	0.750 0.630 0.750	0.710	+5.6 -12.0
7 8 9	0.77	0.4	0.93 1.0 0.95	1.017	+4.1 -3.2
10 11 12	0.63	0.6	1.410 1.39 1.35	1.380	+2.1 -2.2
13 14 15	0.45	0.8	2.000 1.835 1.817	1.884	+6.1 -3.6
16 17 18	0.31	0.9	2.1 2.15 1.87	2.04	+5.4 -9.0

Table 3. Critical pressure for Series-2 (90°, ±30°, 90° winding) partially filled tubes

Test specimen	Ratio of radius (a/R)	Volumetric loading fraction (VLF)	Experimental critical pressure (Mpa)		
			All	Mean	% Variation over mean
1 2 3	1	0	0.595 0.641 0.595	0.610	+5.1 -2.5
4 5 6	0.89	0.2	0.640 0.720 0.660	0.673	+6.9 -5.1
7 8 9	0.77	0.4	0.880 0.920 0.890	0.897	+2.5 -1.4
10 11 12	0.63	0.6	1.140 1.180 1.200	1.173	+0.6 -2.9
13 14 15	0.45	0.8	1.430 1.540 1.460	1.477	+4.3 -3.2
16 17 18	0.31	0.9	1.950 2.220 2.000	2.023	+9.7 -3.7

testing of 20 samples. The mechanical property of the filler material representing HTPB solid propellant of present day rockets, is arrived at after conducting test on the material following ASTM-D638. Shell-181 element having four nodes in each element and six DOF at each node, is used to model S2 glass composite tube. This element allows to define multi-layered composite structure. Solid-186, which is a 3D 20-noded element with quadratic displacement behaviour element and three DOF at each node is utilised to model the inner elastic filler. This solid element has got suitable features to model hyper-elastic solids such as soft elastic filler. Two parameter Mooney-Rivlin model is used to represent the non-linear property of the filler core. Clamped boundary condition is applied on either end of the tubes. Through a mesh convergence analysis 4 mm size of elements are adopted. A non-linear analysis is carried out by applying external pressure load in finite steps till failure. The large deflection option is activated with minimum 50 sub steps for loading. Geometry of the tube and elastic filler are updated at the end of each load step. This geometry update ensured that the external pressure is applied exactly normal to the surface of the updated geometry. FE solution is tracked for each load step. At the bifurcation point, solution starts diverging. This is internally tracked by ANSYS and is indicated as bisection occurrence point which is taken as the point of instability. The maximum radial deflection of the tube is tracked and stored as a function of pressure load till the point of instability. More details about the non-linear FEA procedure and steps are reported in earlier work of the authors[8,9]. As an engineering solution composite rocket motor casings (CRMC) filled with filler such as solid propellant are not allowed to take load beyond a point where initiation of buckling takes place. Since the present investigation aims at studying behaviour of CRMCs, study is limited to the extent of the first fundamental mode shape only. Typical first mode shape for the tubes with L/D=3 is as shown in Fig. 6. Longitudinally it shows one half-sine lobe whereas circumferentially 4-complete lobes are seen for all loading fractions. The mode shape remains unaltered for a given L/D ratio.

4. RESULTS AND DISCUSSION

The critical pressure (Pcr) obtained from pressure-time curves of experiments and pressure-displacement curves obtained from FE analysis are extracted and presented in graphical form in Figs. 7, 8, and 9 corresponding to Series1, Series-2 and Series-3 tubes. For each series of tubes, experimental data spread varies with a maximum limit of 12% which is reasonably good. FEA data match very well with the experimental mean values within a variation of 11 per cent. This gives the confirmation that non-linear FE analysis very closely represents the behaviour of the structure demonstrated in experiments. Enhancement in buckling strength of 0.9 VLF tubes has been 3.5 times for series-1, 2.96 times for series-2 and 1.78 times for series-3 tubes respectively with respect to the corresponding empty tubes. One could clearly see that for all the three series of tubes there is considerable enhancement of buckling strength for an increased VLF.

Further FE analysis based studies are conducted on different L/D ratios of tubes and three different helical angles of winding corresponding to Series 1, 2, and 3 tubes. Results of these analyses are presented in Figs. 10, 11 and 12 for L/D ratios of 1, 3 and 5 respectively. For tubes with VLF of 0.9, changing the winding from a higher angle 45^{O} to a lower angle of 15° has improved buckling strength significantly. The same is true for all the three L/D ratios of tubes but with varying magnitude. Probable reason for such an improvement is the effective longitudinal modulus (Ex) of composite tubes. Higher longitudinal modulus tube takes higher magnitude of support from the inner filling. For a short composite cylinder with L/D=1, gain in buckling strength in presence of propellant is limited to a maximum of 20 per cent over an empty tube. However for cylinders with L/D of 3 and more, which behave as a long cylinder, increment of buckling strength is significant for filled tubes compared to the empty tubes. The inner filling acts as an elastic foundation support to the tubes. Support

Table 4. Critical pressure for Series-3 (90°, ±45°, 90° winding) partially filled tubes

Test specimen	Ratio of radius (a/R)	Volumetric loading fraction (VLF)	Experimental critical pressure (Mpa)		
			All	Mean	% Variation over mean
1	1	0	0.540	0.532	+1.5
2			0.530		-0.38
3			0.525		
4	0.89	0.2	0.570	0.572	+0.35
5			0.574		-0.35
6			0.571		
7	0.77	0.4	0.594	0.595	+0.85
8			0.600		-0.84
9			0.590		
10	0.63	0.6	0.730	0.747	+3.1
11			0.740		-2.3
12			0.770		
13	0.45	0.8	0.980	1.016	+3.3
14			1.020		-3.7
15			1.050		
16	0.31	0.9	1.170	1.155	+1.3
17			1.170		-3.1
18			1.120		

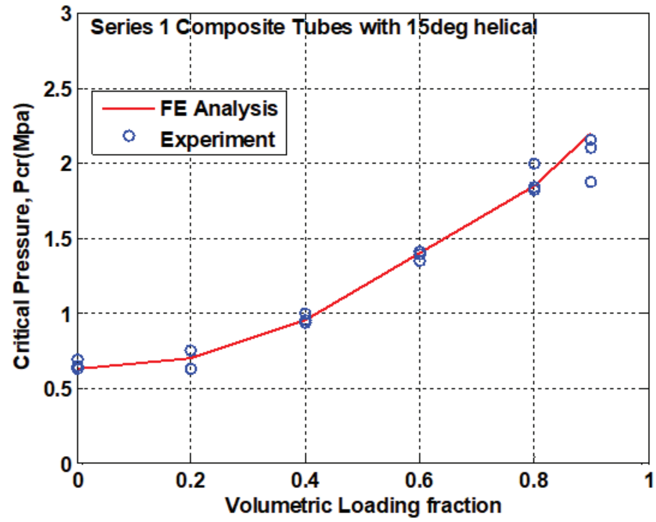

Figure 7. Improvement in critical load for Series-1 tubes.

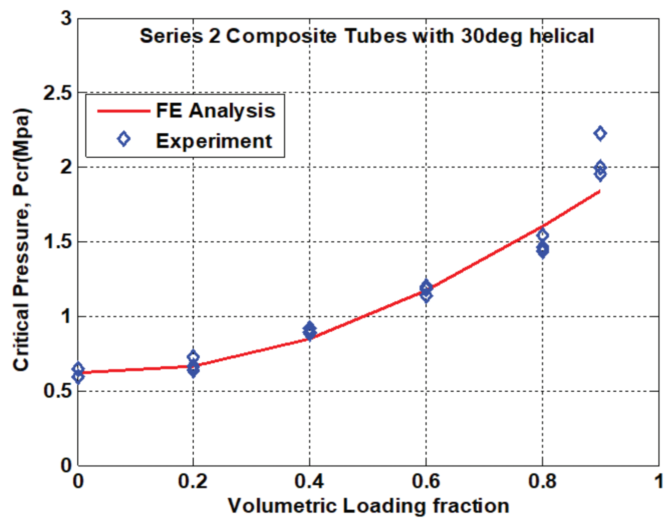

Figure 8. Improvement in critical load for Series-2 tubes.

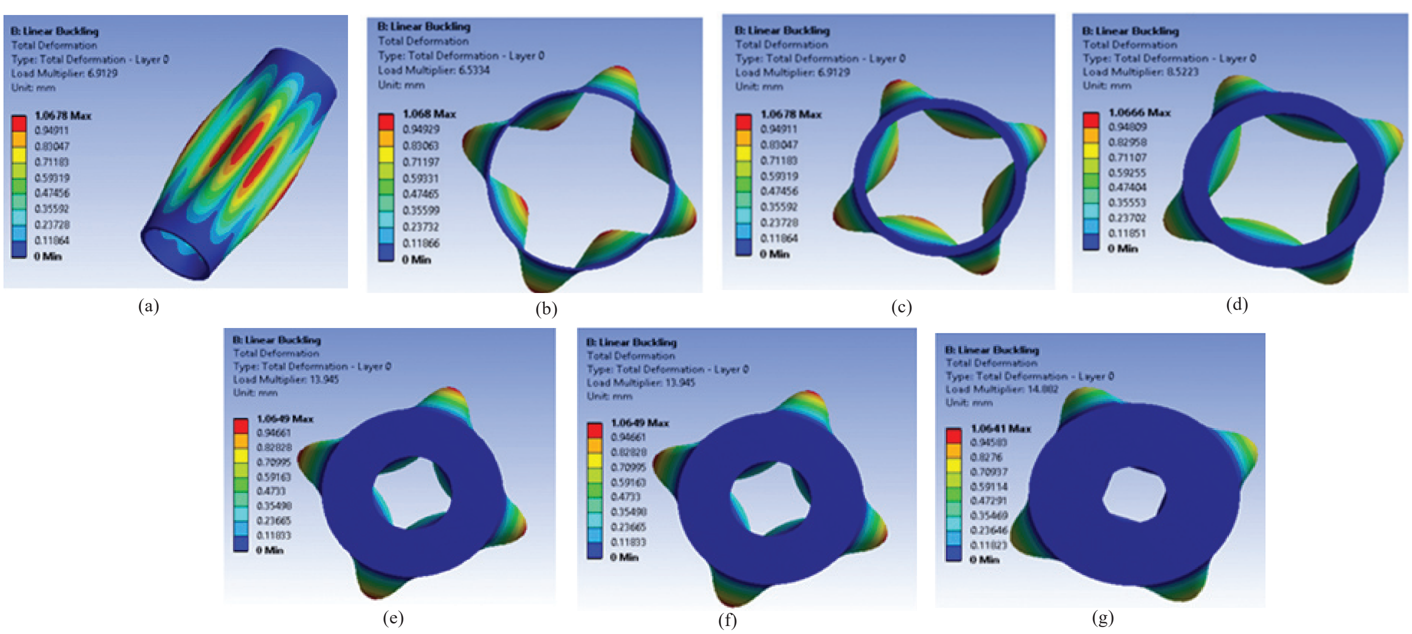

Figure 6. Typical mode shape of filled composite tube (L/D=3): (a) Longitudinal lobe, (b) VLF=0, (c) VLF=0.2, (d) VLF=0.4, (e) VLF=0.6, (f) VLF=0.8, and (g) VLF=0.9.

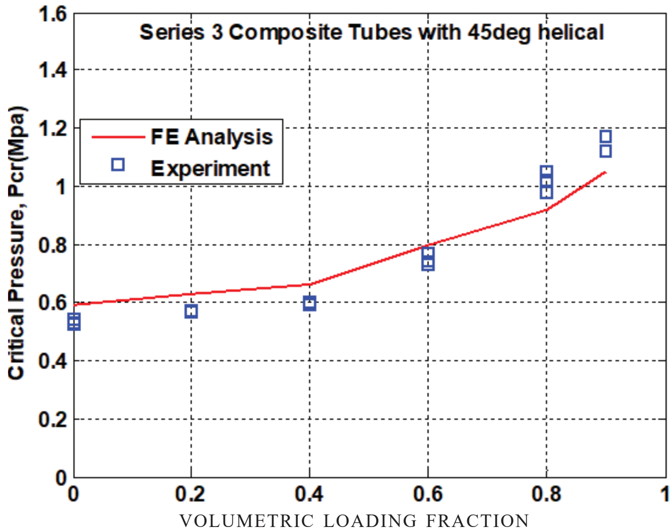

Figure 9. Improvement in critical load for Series-3 tubes.

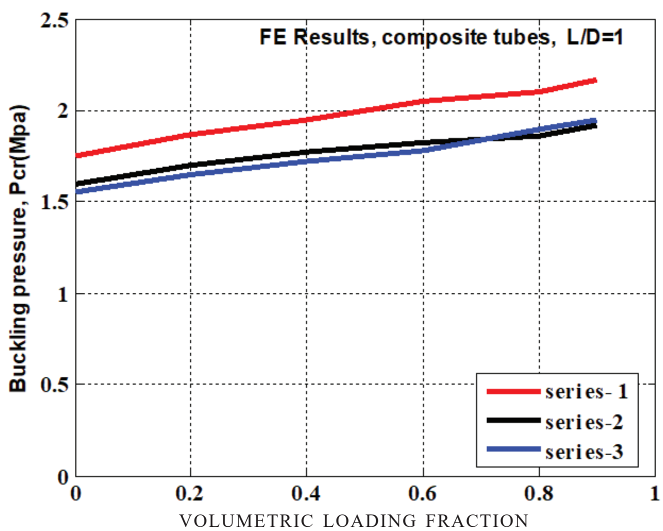

Figure 10. Relative improvement of buckling strength with varying winding angle.

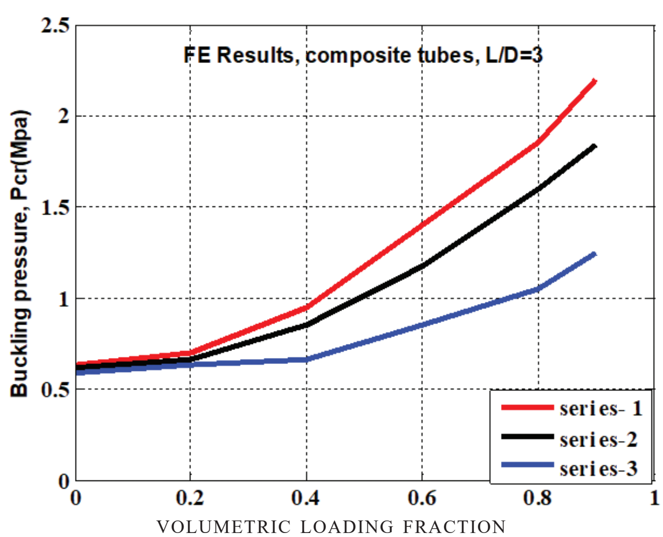

Figure 11. Relative improvement of buckling strength with varying winding angle.

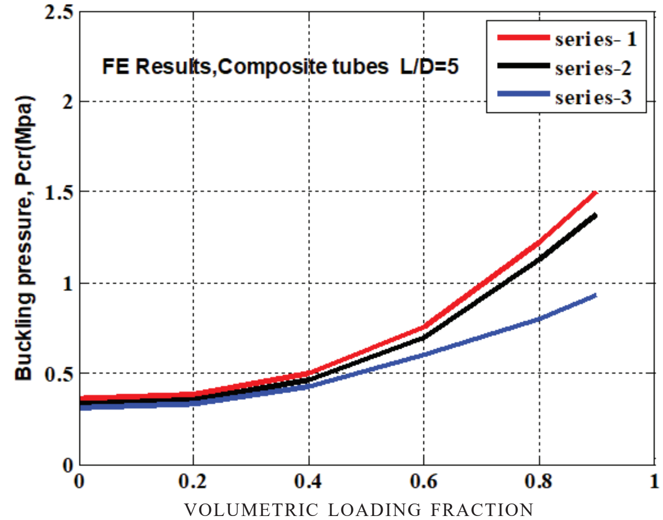

Figure 12. Relative improvement of buckling strength with varying winding angle.

reaction is proportional to the magnitude of radial deflection. Short tubes with low L/D have less radial deflection due to external pressure and hence get less support from the filled core whereas the long tubes derive higher magnitude of support from inner core due to higher magnitude of radial deflection.

5. CONCLUSIONS

Buckling strength of the cylindrical tubes increases significantly for a filled tube in comparison to an empty one. Extent of this increase in strength is a strong function of volumetric loading fraction VLF of the filler material. In case of a high performance rocket motor where VLF is as high as 0.9, buckling strength of composite casings can be expected to improve to an extent of 3.5 time as that of empty casing subjected to external pressure load.

A lower helical winding of 15° increases the buckling strength of a 90 per cent filled tube by 2 time in comparison to a 45° wound one. This increment is due to the increase in longitudinal modulus of the composite tubes for the given choice of winding angles. This stresses the fact that one must choose an optimum helical winding to get best support from the filler material.

For a short composite cylinder with L/D=1, gain in buckling strength in the presence of propellant is limited. However for long cylinders with L/D of 3 and more, increment of buckling strength is significant irrespective of the choice of helical winding angle.

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Contribution in the current study: Guiding and defining all the experiments and scrutinising the results.

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Contribution in the Current Study: Guiding in the area of FE modelling and scrutinising of all FE analysis results.