Fabrication and mechanical behavior of carbon fiber composite sandwich cylindrical shells with corrugated cores

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Abstract

We manufactured sandwich-walled cylinders with longitudinal and circumferential corrugated cores from carbon fiber reinforced composites using a sequential hot press moulding method. As the first step for manufacturing these structures, we fabricated the integral corrugated cores using assembled steel moulds. Then a set of curved sheets was bonded to the corrugated cores to form cylindrical sandwich shells. Axial compression tests were performed on specimens with different geometries to investigate the failure behavior of these structures. For the cylindrical shells with longitudinal cores, both local buckling and face crushing were observed during the experiment with face crushing being the dominant failure mode. For the cylindrical shells with circumferential cores, local buckling was found to be the dominant failure mode. In addition, analytical models pertaining to Euler buckling, shell buckling, face crushing and local buckling failure modes were presented. The models were used to construct failure maps for different specimen geometries. Finally, energy absorption calculation showed that cylindrical shells with longitudinal cores have better energy absorption ability than that with circumferential cores.

Keywords: Cylindrical shell; Corrugated core; failure mechanism maps; Mechanical properties; Axial compression

1. Introduction

Corrugated sandwich structures are widely used in areas of packaging, naval vessel constructions, rocket engine shells and transportation industry due to low manufacturing costs and relatively good mechanical properties [1-2]. There exists significant amount of literatures on the mechanical behavior of corrugated sandwich structures with metallic cores including quasi-static compression [3], in-plane compression [4], bending [5-6] and dynamic response [7-11].

In our previous work, we investigated the mechanical properties and failure mechanism of carbon fiber composite lattice truss structures [12-14]. Corrugated all-composite sandwich structures differ significantly from metal constructions regarding their structural behavior and performance. For instance, Rejab et al [15] presented a series of experimental investigations and computational analysis of the compression response and subsequent failure modes of corrugated sandwich panels made from an aluminum alloy and composite materials. They reported that although the initial failure mode was cell wall buckling, the progression of damage significantly differed between the metallic and composite systems. Investigation of a novel corrugated composite core sandwich panels under out-of-plane quasi-static compressive loading was carried out using analytical, computational and experimental analysis by Kazemahvazi et al [16-17]. The core members, which were themselves sandwich structures had PMI-foam (Rohacell) core and the face sheets of these cores were made from carbon fiber based unidirectional laminates with fiber direction along corrugation. Their investigations revealed that the inherent hierarchy of the structure can be useful in boosting specific strength due to their buckling resistance. Later, Kazemahvazi et al [18] studied the dynamic compressive response of corrugated carbon-fiber reinforcement epoxy sandwich cores using a Kolsky-bar set-up to simulate blast like loading conditions. The tests indicated significant strength enhancements and high speed photography indicated substantial

1 contribution of inertial stabilization of the core members. Jin et al. [19] designed and
2 fabricated a new integrated woven corrugated sandwich composite (IWCSC), aimed to
3 enhance the skin-core debonding resistance of sandwich composite. Their experiments on this
4 structure revealed that the composite, anisotropic nature of the structure activates a number of
5 failure modes leading to a contrast between a stable post peak plateau and brittle failure
6 depending on the direction and type of loading. A corrugated sandwich structure made from
7 glass fiber, carbon fiber and hybrid (glass:carbon=50:50) fiber reinforcement and polymer
8 matrix was investigated for their bending and out-of-plane compression performance by
9 Zhang et al [20]. They found that the hybrid sample with foam insertion showed energy
10 absorption ranging between the glass and carbon fiber composite counterparts, but exhibited
11 highest crush force efficiency. For cylindrical shell with corrugated cores, Fan et al [21]
12 proposed a filament winding and twice co-curing process to make a carbon fiber reinforced
13 composite sandwich cylinder with kagome cores. Axial compression test of these structures
14 showed them to be stiffer and stronger by several times compared to composite cylindrical
15 shell with only outer skin of similar mass [22]. Skin crippling and strength failure were
16 observed to be the competing failure mechanisms of these lattice sandwich cylinders.

17 In the context of the literature mentioned above, to the best of our knowledge, no
18 research work concerning carbon fiber composite sandwich cylindrical shells with corrugated
19 cores has been undertaken till date. In this paper, we present a new manufacturing technique
20 for fabricating all composite cylindrical sandwich structures with corrugated cores and carry
21 out axial compression tests on the fabricated specimens. Details of fabrication of these
22 composite cylindrical shells with corrugated cores are presented and static axial compressive
23 tests are described in Section 2. Analytical models are developed for the axial compressive
24 response of both cylindrical shells with various dimensions and failure mechanism maps are
25 drawn in Section 3. In Section 4, the mechanical properties and failure modes are studied

experimentally along with analysis of the energy absorption ability of the cylindrical shells.

Conclusions are drawn in Section 5.

2. Experimental

2.1 Materials and fabrication

We made the entire cylindrical shell including the face sheets and corrugated core using carbon fiber based LS-3K 0°/90° carbon fiber woven prepreg via hot press moulding technique. The properties corresponding to the woven carbon fiber prepreg used in the study were measured experimentally and listed in Table 1. The entire manufacturing process involved a two-step fabrication process with the first step used to fabricate corrugated cores in longitudinal and circumferential directions. In the next step, we fabricated the curved face sheets using curved steel mould which involved attaching a number of cylindrical face sheets to the cores to complete the fabrication of cylindrical sandwich shells.

2.1.1 Longitudinal corrugated cores

We used a compound mould structure for fabrication due to the complexity of the composite structure especially during the final stages of demoulding. The corrugation is made using a pair of concentric cylindrical steel moulds with grooves in the annular region. We constructed the inner cylindrical mould using a pair of stainless steel trapezoidal prismatic bars which themselves attached to a pair of stainless steel prismatic arcs of same length thus forming a cylinder shaped mould along a central axis, Fig. 1(a). This cylindrical mould was then held together using two circular stainless steel plates, each attached to the top and bottom ends using screws, Fig. 1(b). Note that this particular construction leads to convenient demoulding through unscrewing of the screws, Fig. 1(b). On this assembled cylinder, we attached another set of trapezoidal rib shaped stainless steel moulds in circular pattern using screws, leaving grooves between them, Fig. 1(c). This completed the fabrication of inner part

of the two part mould (mould I). We then placed carbon fiber prepregs, fitting them into the grooves as shown in Fig. 1(d) after brushing a release agent on the mould surface for easy demoulding after curing. In order to make the outer mould, we first affixed trapezoidal prismatic bars (mould II) to mould-I designed to fit into the grooves of mould-I exterior, Fig. 1(e). This ensured that sufficient pressure was exerted on the prepreg during curing. Note that the exposed prepreg between trapezoidal spaces of mould-I and mould II (shown in blue in Fig. 1(e)) would serve as the area of contact for the corrugated core with the inner and outer skin of the sandwich cylinder. We then enclosed this cylindrical structure by a pair of outer semi-cylindrical steel moulds to exert pressure on the surface of the inner assembly as shown in Fig. 1(f) after brushing the release agent on the mould surface. Photographs of the typical parts of the moulds described above are shown in Fig. 2. Finally, we put this assembly into an autoclave and increased the temperature steadily for 45 minutes till it reached 130 °C in vacuum condition and held it at that value for 1.5 hours. This completed the first part of this two-step fabrication process resulting in a corrugated compound structure with longitudinal cores.

2.1.2 Circumferential corrugated cores

We fabricated the circumferential corrugated cores again using a pair of moulds but with somewhat simpler construction. To this end, we assembled the inner mould (mould-I) by laterally fixing several curved stainless steel parts with axially periodic circumferential grooves as shown in Fig. 3(a) with two steel rings at the top and bottom holding the structure in place with screws, Fig. 3(b). This assembly leads to easy demoulding by unscrewing the screws holding the mould in place. Next, we placed carbon fiber woven prepregs over the center mould and enclosed it with semi-cylindrical steel moulds from outside forming the exterior mould (mould-II) as shown in Fig. 3(c-d). We then put the assembly into an autoclave following the same curing procedure as that of longitudinal corrugated cores

described previously. The photographs of various parts of the mould are shown in Fig. 4. Note that as in the previous case, a release agent was brushed on all mould surfaces before curing for convenient demoulding after cure.

2.1.3 Face sheets

The second part of the process involved manufacturing a set of curved face sheets which would form both inner and outer skins of the sandwich cylindrical shells. We made these curved inner skins with woven carbon fiber prepregs using hot press method in a set of curved steel mould shown in Fig. 5(a) matching the different curvatures of the two sides of the structure. This compound construction was held in place using a curved steel plate which affixed to the remaining structure at both the top and bottom ends through screws, Fig. 5(b). This process would be used to fabricate a total of three pair of face sheets, each with angular span of 120° to complete the circular span of the two face sheets. Note that this three part construction which would theoretically lead to cylindrical face sheets on final assembly would still leave gaps in the seams where these face sheets (principal face sheets) would meet. This gap could result in premature failure of the structure by nucleating fractures. This would be remedied by using three pairs of reinforcing face sheets at the seams (three each for outer and inner principal face sheets) before final assembly with the corrugated core as shown schematically for both types of cores in Fig. 6(a). Note that before assembly we used a *J-242A* film adhesive (manufactured at *Heilongjiang Institute of Petrochemical*), slicing them into thin layers and placing them on the ribs of the corrugated cores where the core met the face sheets. The final configuration of the structure before the final co-cure is shown through a perspective and axial view for the longitudinal core in Fig. 6(b) indicating the position of the corrugated core, the face sheets and the reinforcing sheets. We then put this assembly into an autoclave and cured at 120°C in vacuum condition for one hour thus completing the entire manufacturing process. Photographs of the fabricated cylindrical shell with longitudinal and

circumferential corrugated cores and the final composite structure are shown in Fig. 7(a-d)

The critical parameters describing the geometry of the unit cell of curved longitudinal corrugated cores are sketched in Fig. 8. Thus, from the geometry of the unit cell, the relative density of longitudinal corrugated cores can be shown to be:

$$\bar{\rho}_l = \frac{2t_f(2R+2t_f+h_c) + \frac{2n}{\pi}t_c(s_1+s_2)}{(R+2t_f+h_c)^2 - R^2} \quad (1)$$

For circumferential corrugated cores, the critical parameters are sketched in Fig. 9. Thus, from the geometry of the unit cell, the relative density of circumferential corrugated cores can be shown to be:

$$\bar{\rho}_c = \frac{2t_f \frac{L}{n} + 2t_c(s_1+s_2)}{\frac{L}{n}(2t_f+h_c)} \quad (2)$$

where $R, t_f, t_c, h_c, n, s_1, s_2$ are geometrical parameters shown in Fig. 8 and Fig. 9 and n is the number of corrugations. For the current work, we used the following geometrical parameters, $L=180$ mm, $R=58$ mm, $h_c=11$ mm. Furthermore, for the longitudinal corrugated cores, $t_f=t_c = 0.70$ mm or 0.46 mm, $s_1=6$ mm, $s_2=12$ mm, and $n=15$ which leads to a relative core density 22.1% or 18.0%. The total weight of the cylindrical shells with longitudinal corrugated cores specimen in the following section is about 300 g or 215g and its geometrical parameters are listed in Table 2. On the other hand, for the circumferential corrugated cores, $t_f=t_c = 0.72$ mm or 0.48 mm, $s_1=6$ mm, $s_2=16$ mm, and $n=4$ which leads to a relative core density 16.9% or 12.0%. The total weight of the cylindrical shells with circumferential corrugated cores specimen in the following section is about 280 g or 200g and its geometrical parameters are also listed in Table 2.

2.2 Experimental setup

We conducted quasi-static axial compressive tests on the fabricated sandwich-walled cylindrical shell specimens using an electro hydraulic servo system universal testing machine Instron (with capacity of 20 tons), the applied strain rate is 0.5mm/min. Prior to the tests, we clamped both ends of the cylinders using stainless steel flange plates. The strain was estimated by placing several strain gages along the inner and outer skins of the sandwich cylinder. In total, there were 8 strain gages spread across inner and outer skins of each specimen to measure axial and transverse strains during loading. We clamped the specimen in the annular groove of the stainless steel plates and injected an epoxy resin into both ends of the cylindrical shell to avoid end failure.

3. Analytical models of axial compressive behaviors

3.1 Analytical predictions

The following possible failure modes of an all-carbon sandwich cylindrical shell under axial compression are studied in this section - (a) Euler buckling (EB), (b) Shell buckling (SB), (c) Local buckling (LB) and (d) face crushing (FC). Similar analytical investigations have been performed previously for composite sandwich structures with lattice cores under both axial and bending loads [23-24]. Below, we derived analytical expressions of each failure modes for cylindrical shells with longitudinal corrugated cores (Section 3.1.1) and with circumferential corrugated cores (Section 3.1.2).

3.1.1 Cylindrical shells with longitudinal corrugated cores

Euler buckling (EB) o: The Euler buckling load denoted by P_{EB} , can be expressed as,

$$P_{EB} = \pi^3 E_f \frac{2t_f + \sqrt{2}t_c}{2t_f + h_c} R^4 \left[\left(\frac{R + 2t_f + h_c}{R} \right)^4 - 1 \right] \frac{1}{L^2} \quad (3)$$

where R is the radius of inner face sheet, h_c is the height of core and L is the height of the

cylinder. E_f is Young's modulus of the inner and outer face sheets with same stake sequences, t_f denotes the thickness of the inner and outer face sheets, which in this work, are assumed to be equal for both face sheets.

Shell buckling (SB): The shell buckling load denoted by P_{SB} , can be estimated from,

$$P_{SB} = 1.2\pi(E_{f1} + E_{f2}) \frac{t_f}{h_c + 2t_f} \frac{(h_c + 2t_f)}{(R + h_c + 2t_f)} R t_f \quad (4)$$

where E_{f1} and E_{f2} are the Young's modulus of the inner and outer face sheets separately and all other parameters are shown in Fig. 8 and the above section.

Local buckling: This failure mode is different from the mentioned buckling modes studied previously [24]. This is because in the present case, local buckling occurs between the bonding areas of longitudinal corrugated cores. The boundary conditions for local buckling are obtained by assuming that four sides are in simple support. This assumption would give us more conservative failure values. In our study, we assumed that the face sheets behave elastically and the length of the plate is more than $\sqrt{2}$ times of the width of the plate. We assumed that x and y axis are the longitudinal and circumferential direction respectively and the curvature effects were neglected for this rather small domain. Next, we can get the plane

stress as $\sigma_y = -\frac{F_y}{t_f}$, $\sigma_x = 0$, $\tau_{xy} = 0$, which leads us to write the internal force in the face as

$F_{Ty} = -F_y$, $F_{Tx} = 0$, $F_{Txy} = 0$. Substituting them into the plate deflection equation [25], we can

get $D\nabla^4 w + F_y \frac{\partial^2 w}{\partial y^2} = 0$, $D = \frac{E_f t_f^3}{12(1-\mu^2)}$ is the bending stiffness of the plate and μ is the

posson ratio, w is defection and y is the deflection along circumferential direction. We

express the deflection expressions as $w = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \sin \frac{m\pi x}{b} \sin \frac{n\pi y}{a}$ which will satisfy the

boundary conditions at four edges. The minimum critical load can be derived from the above

equations as $F_y = k \frac{\pi^2 D}{b^2}$ with $k=4$ for the plate with clamped boundary conditions [25].

Thus, the failure force in our case would be $F_y = \frac{\pi^2 k E_f t_f^3}{12(1-\mu^2)b^2}$. When $\mu=0.3$ and $k=4$, the critical buckling force P_y can be written as:

$$P_y \approx 0.72 \frac{\pi^3 E_f t_f^3 (2R + \sqrt{2}R + h_c)}{b^2} . \quad (5)$$

Face Crushing (FC): This mode of failure occurs when the cylindrical shell fails with the crushing of either skins or corrugated core with the associated failure loads that can be estimated from the following equation by considering the contribution of both face sheets and corrugated cores:

$$P_{FC} = 2\pi \left[\left(2 + \sqrt{2} \right) R + h_c \right] \sigma_f \quad (6)$$

where P_{FC} is the critical force for instability, σ_f is the crushing strength of the inner and outer face sheet material. In our paper, the crushing strength of the inner and outer face sheet materials was obtained from Table 1 as $\sigma_f = 393.34 \text{ MPa}$.

3.1.2 Cylindrical shells with circumferential corrugated cores

Euler buckling (EB) of cylindrical shells:

$$P_{EB} = \pi^3 E_f \frac{2t_f}{2t_f + h_c} R^4 \left[\left(\frac{R + 2t_f + h_c}{R} \right)^4 - 1 \right] \frac{1}{L^2} \quad (7)$$

Shell buckling (SB):

$$P_{SB} = 4C\pi(1+k) \frac{E_f t_f^2 (2R + h_c)}{(R + h_c + 2t_f)} \quad (8)$$

where the value of K_{cf} is determined based on the boundary conditions between skin and cores .

Local buckling(LB): Local buckling occurs between the bonding area which is a short cylindrical shell with circumferential corrugated cores. The buckling strength of this kind of structure is different from the classical analytic solution since the height is significantly lesser compared to its radius. We now introduce a parameter $\lambda = \sigma_x / \sigma_{c1}$, (available in literature [26]) where σ_x is the buckling strength of the short cylindrical shell and σ_{c1} is the classical critical strength of a cylindrical shell. From this, we get the critical load of local buckling as

$$P_{LB} = \frac{2\pi(1+k_{cf})(2R+h_c)Et}{3} \frac{l^2}{R^2}, \text{ when } l/\sqrt{Rt} \leq 1 \quad (9)$$

$$P_{LB} = 1.2\pi(1+k_{cf}) \frac{E_f t^2 (2R+h_c)}{(R+h_c)\sqrt{3(1-\mu^2)}}, \text{ when } l/\sqrt{Rt} > 1 \quad (10)$$

Face Crushing(FC):

$$P_{FC} = 2\pi(1+k_{cf})(2R+h_c)t_f\sigma_f \quad (11)$$

The geometrical parameters used in this equation have been mentioned above and the value of σ_f is listed in Table 1.

3.2 Failure mechanism maps

From the above discussions, it is clear that several types of failure modes may result depending on the geometry, material and loading. In order to illustrate the dominant failure modes of sandwich-walled cylinder, we constructed failure mechanism maps on a plane defined by a pair of normalized geometric axes based on the lowest failure load as predicted by the analytical models presented above. Fig. 10 shows the failure mechanism map for all composite sandwich cylindrical shells with longitudinal corrugated cores. Similarly, Fig. 11 shows the failure mechanism map for all composite sandwich cylindrical shells with circumferential corrugated cores. For the cylindrical shells with longitudinal corrugated cores, the large fonts denote the three dominant failure regions LB, EB and FC corresponding to the initial failure.

4. Results and discussion

4.1 Elastic response and failure modes

In this section we discuss the experimental results from the axial compression test described above. Recall that there are two types of composites: cylindrical shells with longitudinal and circumferential corrugated cores. We call them respectively longitudinal and circumferential type composites for brevity. For testing, we fabricate two kinds of specimens for each composite type corresponding to two different thicknesses of the skins. Furthermore, each kind of specimen is fabricated in duplicate for consistency thereby resulting in a total of eight test specimens.

The failure process will be addressed in details in the following section. To this end, we plot the strain-time characteristic and the corresponding load-displacement behavior during axial loading. In the load-displacement response, we delineate general configuration of the structure at each distinct loading phase with roman numerals and use visual photographic evidence of the structure at those loading instants for the sake of greater clarity. Since each kind of specimen had two test samples, there we two set of data. However, since their behavior was very similar, only one of the specimens from each set would be discussed for brevity.

In the course of our experiments, we did not observe global buckling due to the short length of our specimens. Similarly shell buckling mode, with its distinct morphology and which would have led to a catastrophic failure was also not observed. On the other hand, LB which could occur between bonding area of longitudinal corrugated cores was observed using both strain gages and visual inspection. Similarly, crushing failure was easily observed through visual inspection, load measurements and strain gages due to its dominant nature (precipitating fracturing and delamination).

4.1.1 Cylindrical shells with longitudinal corrugated cores

We first tested longitudinal type composite specimens with skin thickness of 0.70mm under axial load. The strain history is illustrated in Fig. 12 and typical mechanical response curves and the photographic illustration of corresponding failure modes are shown in Fig. 13.

From the strain history, we note that the axial strain values of the both inner (strain gages 8) and outer (strain gages 2, 4, 6) skin are negative indicating compressive state of strain, whereas all the transverse strain values of outer skin (strain gages 1, 3, 5) are positive indicating tensile conditions. The tensile conditions result due to the bulging of the shell under axial compression.

As the load was ramped up, the axial strain gages on outer face sheet labeled 2 and on inner face sheet labeled 8 changed slightly around 125 s indicating some degree of LB. However, overall little anomalous behavior of individual strain gages was observed until about 130s thus indicating a remarkable suppression of LB. However, some strain gages showed some deviation from linearity possibly due to the bulging effect. Then, after 130 s, this monotonic strain-time behavior gave way to sudden simultaneous change in the inner (strain gage 8) and outer face axial strains (strain gages 2, 4, 6 and 7) indicating local fracture of inner and outer face sheets after which all the strain gages were stopped to record the strain values. The dashed line approximates the threshold of failure for the specimen. Note that strains during the actual crushing event which occurs at around 130 s cannot be recorded due to distortion to the strain gage set up due to widespread damage.

The load-displacement behavior of these specimens, quantified in Fig. 13(a) with photographs of specific points of observation presented in Fig. 13(b) also confirms these observations. The load-displacement curve of the representative specimen 1 shows that as the specimen was loaded in axial compression, no significant deviation from linear behavior (point I, Fig 13(a),(b)) is observed till about 129 kN (peak load). As the load reached near this

value, low intensity pinging noises which had started to emanate from the sample some time before increase appreciably. We believe that the low intensity pinging noises arose from the composite faces due to local failure of matrix and fibers since significant structural collapse did not accompany these noises. In addition, noises emanating from the core would be more muffled. Thereafter, there was a sudden drop in load bearing capacity of the structure due to the onset of significant face sheet crushing. We note that the double face sheets of the sandwich structure restrain LB of corrugated core and failures are transferred to the face sheets, which results in enhancements in the load capacity. As loading progressed, fracturing started along fiber direction and craze penetrated throughout the cylindrical shell, point II (Fig. 13(a),(b)). The direction of craze in outer face sheet is almost circumferential, point II, Fig. 13(b). Thereafter, further fracture and delamination of both skins significantly deplete the load bearing capacity of the structure as seen in the sharp drop after point III (Inset-Fig. 13(a), Fig. 13(b)). This decline in load bearing capacity is arrested as densification of the overall cylindrical shell starts leading to eventual rapid hardening (point IV, inset-Fig. 13(a), Fig. 13(b)).

Next, we tested longitudinal type composite specimens with skin thickness of 0.46 mm under axial load. Thus these specimens were considerably thinner than the previous specimens. The strain history of a representative specimen is illustrated in Fig. 14 and the photographic illustration of corresponding failure modes of the specimen are shown in Fig. 15. It can be seen from Fig. 14 that all axial strain values at the outer surface of the cylinder were negative indicating compressive state whereas the transverse strain values (strain gages 1, 3, 5) were positive, indicating tensile state due to bulging, similar to the thicker specimen. The strain variation for all strain gages were linear until the load increased till about 110 s at which point the slope of strain gages 1 and 2 changed sharply while other strain values experienced a small jitter, which indicates the gages 1 and 2 suffered large deformation in

isolation suggesting LB failure. Interestingly, although LB was observed, it did not cause a total loss of load bearing capacity of the structure and thus the cylinder continued to resist loading. The strain gages thus continued to show a corresponding increase with loading progression until at about 160s where all of them collectively suffered large changes due to the dominant failure mode. The experiment was stopped at this point and the strain values recorded. Note that although LB did not result in the ultimate collapse of the structure, in general it does influence the final failure mode by accelerating the onset of FC which was the dominant failure mode.

The failure response is further illustrated by the load-displacement diagram and photographic evidence of the representative specimen 1 in Fig. 15 (a,b) . Like the corresponding thicker sample, this sample also exhibited an initial linear regime (point I, Fig. 15 (a), (b)) till reaching a peak load of about 67.3 kN after which there was a sudden drop in load bearing capacity due to the dominant FC mode of failure. It is interesting to note that the LB detected by jitters in our strain gage measurements previously failed to cause perceptible deviation from linearity (point I, Fig. 15(a), (b)). After the peak load was reached, fracture and delamination of both skins occurred as confirmed through load measurements (point II, Fig. 15(a)), visual inspection (point II, Fig. 15(b)) and strain gage measurements discussed earlier. The progressive fracturing of the skins mirrored the load displacement behavior which showed a gentle slope after point II via point III (Fig. 15(a), Fig. 15(b)) up until Point IV (Inset-Fig. 15(a), 15(b)). As failure proceeds further, this gentle slope then gives way sharp decline in load bearing capacity due to rapid collapse of the structure (point IV to point V, Inset Fig. 15(a), Fig. 15(b)). This sharp decline is arrested as densification of the overall cylindrical shell starts leading to eventual rapid hardening after point V.

4.1.2 Cylindrical shells with circumferential corrugated cores

In this section, we describe the axial compression behavior of circumferential type composite specimens. As before, specimens of two different average face sheet thicknesses (0.72 mm and 0.52 mm) were used. First, we studied the behavior of cylindrical shells with 0.72 mm face sheet thickness. The strain history of this sample is shown in Fig. 16, and the typical load-displacement response curve and photographic illustration of failure modes of the specimen were shown in Fig. 17 (a), (b). It can be seen from Fig. 16 that all the axial strain (strain gages 2, 4, 6 and 7) value at the outer surface was negative indicating compressive state and the transverse strains (strain gages 1, 3 and 5) were either too small or positive indicating some effect of bulging as discussed previously.

As loading proceeds, we find that all the strain gages experience a jitter at about 75s which indicates the face sheet has suffered widespread deformation. However, this does not indicate a terminal failure mode such as face sheet crushing or Euler buckling since the structure continued to bear load. Thus we conclude that this indicates widespread LB. At about 90 s, the strain-time curve give way to sudden large change indicating total failure. A post-mortem visual inspection indicated that the dominant failure mode was essentially widespread LB mode of failure.

In order to investigate the load bearing capacity of the structure, we plotted the axial load-displacement characteristics in Fig. 17. We note from this figure that as the specimen was loaded in axial compression, no significant deviation from linear behavior (point I) is observed till about 78 kN (point II, Fig. 17(a), (b)). At about 78kN, the stiffness begins to decrease indicating that the specimen has begun to accumulate damage. In this context, earlier strain gage measurements and visual inspection, point II, Fig. 17 (b) indicated the origin of this damage to be primarily contributed by increasing LB. Thereafter, as LB spread, the stiffness continued to decrease until a peak load of 90.6 kN was reached followed by a

sudden drop in load due to the widespread LB. With a corresponding increase in displacement, further drop in load bearing capacity of the structure was observed, point III, Fig. 17(a). This can be primarily attributed to the FC at the part of face sheet where LB previously happened, clearly observed visually, point III, Fig. 17(b). With further increase in the applied load, fracturing and delamination occurred (point IV – inset Fig. 17(a), Fig. 17(b)), which ultimately gave way to densification of the cylindrical shells (point V, Fig. 17(b)) leading to significant hardening as seen in point V, Inset-Fig. 17(b). Thus from these tests, we can conclude that the failure process was precipitated through LB leading thereafter to large local deformation and crack appearance. The structure began to lose integrity as the cracks started to propagate rapidly with load.

Next, we describe axial compression behavior of the thinner specimen (face thickness of 0.52mm). The strain history for this sample is shown in Fig. 18, and the typical load-displacement response curve and photographs of failure modes of the specimen are shown in Fig. 19 (a,b). From the strain-time plot of Fig. 18, we observe that all the axial strain values at the outer surface which were negative suffered a jitter at about 400 s shown in Fig. 18. Since the structure continued to bear load, it indicates that the face sheet had experienced considerable local failure. At about 450 s, the strain-time behavior shows a sudden large change across all strain gages indicating that the structure had collapsed due to widespread LB.

In order to gain insight into the load bearing capacity of this structure, we plot the load displacement relationship in Fig. 19(a) and exhibit the photographic evidence at different points of loading in Fig. 19(b). Fig. 19(a) clearly shows that as the specimen was loaded in axial compression, no significant deviation from linear behavior (point I and point II) was observed till about 40kN, after which stiffness degradation became perceptible. Thereafter at about 40 kN (peak load) there was a sudden drop in load bearing capacity of the

structure, point III, Fig. 19(a) due to the onset of significant LB as evidenced by visual inspection, point III, Fig. 19(b). Therefore, LB is the dominant failure mode near peak load and with increasing displacement, continuing drop in load bearing capacity of the structure is observed, point IV Inset-Fig. 19(a), due to fracturing and delamination of skins due to large deformation of LB sites, point IV, Fig. 19(b). As the displacement was further increased, widespread failure lead to densification and corresponding hardening of the structure, point V, Inset-Fig. 19(a), Fig. 19(b).

4.2 Comparison with analytical model

The comparison between the analytically developed model and experimental results is shown in Table 2 which shows a good agreement for the failure modes. In this context, juxtaposing the failure locus of our designed samples on the failure mechanism map indicates LB to be the failure mode, Figs. 10, 11. However note that since LB is not a terminal failure mode, it could essentially coexist with FC till the later precipitates complete failure. This is in agreement to our experimental observations described earlier, which showed the final collapse mechanism of the cylinder to be FC. For the longitudinal type specimens, the FC mode was apparent due to either suppressed or isolated LB. On the other hand for the circumferential type specimens, extensive LB first occurred creating localized bulged areas and then FC appeared at those localized bulging sites.

In contrast to this good agreement with failure mode prediction, the experimental peak load value was smaller than analytical values. There are several possible reasons for this disagreement: (1) the simplifying assumptions on materials and geometry used in the model and discussed earlier, (2) the gaps left between curved face sheets during fabrication, which introduced an imperfection in the sample leading to reduction of the critical load and (3) other defects due to fabrication and (4) neglect of interaction between co-existing damage modes.

4.3 Energy absorption in quasi-static uniform compression

In this section, we analyze the energy absorption characteristic of the fabricated structure. To this end, first, we calculate the amount of absorbed energy by integrating the curve of the load-displacement from the origin of coordinates to the turning point where curve began to rapidly rise due to significant densification. We now use the experimental data from load-displacement curve to compute the energy.

From Figs 13(a) and 15(a), the compression curves for longitudinal corrugated cores reveal long deformation plateaus which indicate that the carbon fiber composite sandwich cylindrical shells with longitudinal corrugated cores may potentially be good energy-absorbing structure. We find that for the structure, the specific energy absorption of the specimen with face sheet thickness = 0.7 mm, is 33.54J/g (Fig. 13(a)) and for specimen with face sheet thickness = 0.46 mm is 27.9J/g. (Fig. 15(a)). On the other hand, it is clear from the shape of the load-displacement characteristic of the carbon fiber composite sandwich cylindrical shells with circumferential corrugated cores, that the energy absorption is far less favorable. This is because from Fig. 17(a) and Fig. 19(a), we can see the bearing load remains low after it falls from the peak load. For the two specimens, which had average thickness of face sheets were 0.48 and 0.72mm, the integral corresponding to the shaded area in Fig. 17(a) and Fig. 19(a) gives us absorbed energy $W=3.2$ J/g (Fig. 17(a)) and 6.45 J/g (Fig. 19(a)) respectively. Clearly, this is much lower than carbon fiber composite sandwich cylindrical shells with longitudinal corrugated cores. One of the reasons for this large discrepancy is that, for the longitudinal samples, even after the failure of face sheets, they can still bear significant amount of load unlike the circumferential corrugated cores.

5. Conclusions

In this paper, we fabricated and studied the mechanical response and failure of carbon fiber composite sandwich-walled cylindrical shells with corrugated cores under uniaxial

compression. Both vertical and circumferential corrugated core were made using steel mould. We carried out both analytical calculations and direct experimental tests on the fabricated cylinders. The strain and failure mechanism were investigated in detail in our experiments. Both local buckling between bonding areas and face crushing have been found in the experiments of cylindrical shells with longitudinal corrugated cores. As for cylindrical shells with circumferential corrugated cores, we found the role of local buckling to be more pronounced as it precipitated the catastrophic crushing mode through large local deformation. Finally we calculated the energy absorption of both kinds of specimen and conclude that the cylindrical shells with longitudinal corrugated cores have better energy absorption capacity under quasi-static uniaxial compression than that with circumferential corrugated cores.

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Tables

Table 1 Properties of carbon fiber woven fabric		
Materials	E_f (GPa)	σ_f (MPa)
LS-3K 0°/90° carbon fiber woven composite	51.5	393.34

Table 2Analytical and Experimental results for the failure behavior of fabricated samples

Specimen	Face thickness	Mass (g)	Analytical failure modes loads (kN)		Experimental failure load (kN)		Experimental failure modes observed
Longitudinal corrugated cylindrical shells	0.70mm	300	EB	152385.53	Specimen 1	130.5	LB FC
			SB	365.50			
			LB	87.22	Specimen 2	129.8	
			FC	285.114			
	0.46mm	215	EB	98957.09	Specimen 3	67.3	LB FC
			SB	158.91			
			LB	24.75	Specimen 4	66.9	
			FC	187.361			
Circumferential corrugated cylindrical shells	0.72mm	280	EB	116952.4	Specimen 5	90.6	LB
			SB	164.5			
			LB	122.0	Specimen 6	89.9	
			FC	245.9			
	0.48mm	200	EB	70115.03	Specimen 7	40.4	LB
			SB	73.67			
			LB	54.22	Specimen 8	38.4	
			FC	163. 92			

Figures

Figure 1 Fabrication process for carbon fiber composite longitudinal corrugated cylindrical cores. (a) Center mould, (b) Center mould fixed by steel cover, (c) Trapezoid rib shape mould I assembled with center mould, (d) Placing carbon fiber composite prepregs into surface of rib shape mould I, (e) Assembling rib shape mould I and II together, (f) Enclosing the core structure with a pair of outer semi circumferential steel moulds.

Figure 2 Photographs of the mould of sandwich-walled cylindrical shell with longitudinal corrugated cores.

Figure 3 Fabrication process for carbon fiber composite circumferential corrugated cylindrical cores. (a) Center mould, (b) Center mould fixed by steel cover, (c) Placing carbon fiber composite prepreg on the center mould, (d) Enclosing the core structure with a pair of outer semi circumferential shape steel moulds.

Figure 4 Photographs of the mould sandwich-walled cylindrical shell with circumferential corrugated cores: (a) center mould, (b) complete set of mould.

Figure 5 (a) 3-D schematic view of both inner and outer face sheet fabrication. (b) Photographs of curved steel mould for both inner and outer face sheets.

Figure 6 Individual components and final assembly of the carbon fiber composite sandwich walled cylinder with longitudinal and circumferential corrugated cores. (a) Perspective view of adhesive process of curved face sheet and (left) longitudinal as well as (right) circumferential corrugated cores, (b) schematic (left) perspective view and (right) axial view of final assembly of the longitudinally corrugated assembly before curing.

Figure 7 (a) Carbon fiber woven composite longitudinal corrugated shell, (b) Carbon fiber woven composite sandwich cylindrical shells with longitudinal corrugated cores, (c) Carbon fiber woven composite circumferential corrugated shell, (d) Carbon fiber woven composite sandwich cylindrical shells with circumferential corrugated cores.

Figure 8 Geometrical parameters of the unit cell of curved longitudinal corrugated cores

Figure 9 Geometrical parameters of the unit cell of curved circumferential corrugated cores

Figure 10 Failure mechanism maps for composite cylindrical shells with longitudinal corrugated cores

Figure 11 Failure mechanism maps for composite cylindrical shells with circumferential corrugated cores

Figure 12 Strain history of both inner and outer face sheets with thickness of 0.70 mm

Figure 13 Mechanical properties and failure modes of a carbon fiber composite cylindrical shell with longitudinal corrugated cores (face thickness =0.70 mm).

Figure 14 Strain history of both inner and outer face sheets with thickness of 0.46 mm

Figure 15 Mechanical properties and failure modes of a carbon fiber composite cylindrical shell with longitudinal corrugated cores (face thickness =0.46 mm).

Figure 16 Strain history of both inner and outer face sheets with thickness of 0.72 mm.

Figure 17 Mechanical properties and failure modes of carbon fiber composite cylindrical shell with longitudinal corrugated cores (face thickness =0.72 mm).

Figure 18 Strain history of both inner and outer face sheets with thickness of 0.48 mm.

Figure 19 Mechanical properties and failure modes of carbon fiber composite cylindrical shell with circumferential corrugated cores (face thickness =0.48 mm).

Figure 1

- a)** Center mould with steel cover **b)** Outer semicircular steel moulds

- c)** Trapezoid rib shape mould I **d)** Trapezoid rib shape mould II

Figure 2

Figure 3

a) Center mould

b) Complete set of mould

Figure 4

a) carbon fiber composite prepreg

b) Curved steel

Steel cover

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16

Figure 17

Figure 18

Figure 19