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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 experiments 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 those with circumferential cores.

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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 and Cantwell [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 contribution of inertial stabilization of the core members. Jin et al. [19] designed and fabricated a new integrated woven corrugated sandwich composite (IWCSC), aimed to enhance the skin-core debonding resistance of sandwich composite. Their experiments on this structure revealed that the composite, anisotropic nature of the structure activates a number of failure modes leading to a contrast between a stable post peak plateau and brittle

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failure depending on the direction and type of loading. A corrugated sandwich structure made from glass fiber, carbon fiber and hybrid (glass:carbon = 50:50) fiber reinforcement and polymer matrix was investigated for their bending and out-of-plane compression performance by Zhang et al. [20]. They found that the hybrid sample with foam insertion showed energy absorption ranging between the glass and carbon fiber composite counterparts, but exhibited highest crush force efficiency. For cylindrical shell with corrugated cores, Fan et al. [21] proposed a filament winding and twice co-curing process to make a carbon fiber reinforced composite sandwich cylinder with Kagome cores. Axial compression test of these structures showed them to be stiffer and stronger by several times compared to composite cylindrical shell with only outer skin of similar mass [22]. Skin crippling and strength failure were observed to be the competing failure mechanisms of these lattice sandwich cylinders.

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

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

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

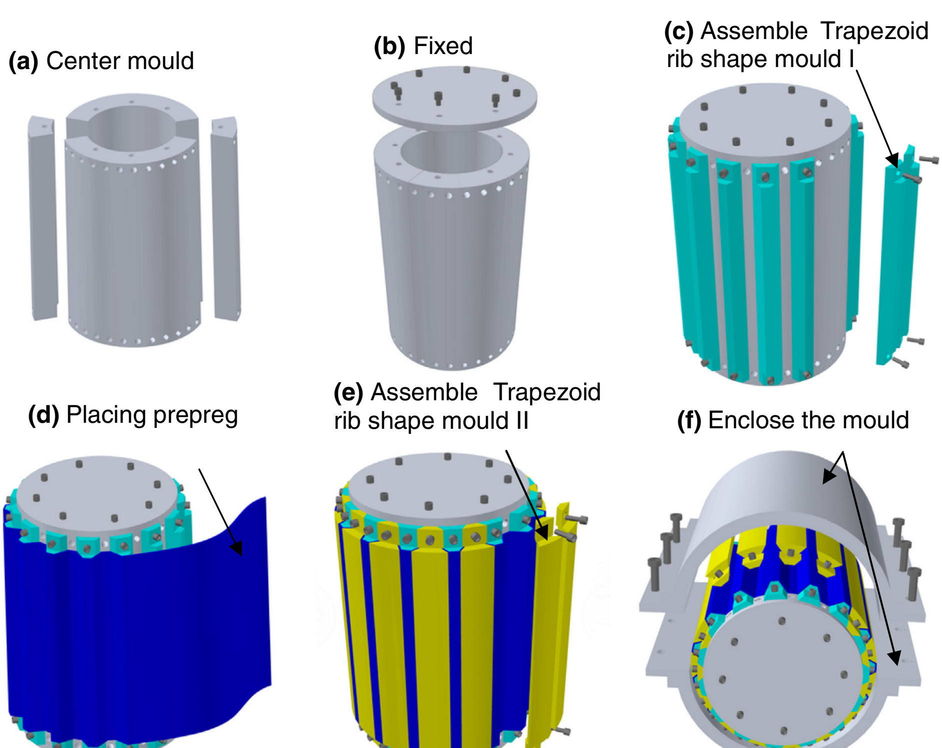

Fig. 1. Fabrication process for carbon fiber composite longitudinal corrugated cylindrical cores. (a) Center mould, (b) center mould fixed by steel cover, (c) trapezoid rib shape mould I assembled with center mould, (d) placing carbon fiber composite prepregs into surface of rib shape mould I, (e) assembling rib shape mould I and II together, (f) enclosing the core structure with a pair of outer semi circular steel moulds.

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