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Dynamic compressive response of wrapped carbon fibre composite corrugated cores

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ABSTRACT

The experimental study on the compressive response of the carbon fibre composite sandwich structures with corrugated cores is reported. The corrugated core was manufactured from unidirectional carbon fibre pre-impregnated lamina wrapped around destructible triangular prisms. Individual wrapped triangular composite cores of relative density $\bar{\rho} \approx 0.13$ are cut from the sandwich beams and tested under both quasi-static compression and dynamic compression at a strain rate up to 8200 s^{-1} using an instrumented direct impact Kolsky bar experiment. Under quasi-static compressive test, as the cores were provided with no lateral confinement, the failure mechanism of the composite core was that of progressive unwrapping of cores due to matrix cracking at the joints of the core webs. Under the dynamic compressive tests, the composite cores demonstrated rate-dependent behaviour. The strain rate dependency was attributed to the suppression of the quasi-static "unwrapping" failure mechanism, and inertial stabilisation of the struts against buckling leading to an upper-bound failure mechanism of crushing of carbon fibre material within the struts.
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1. Introduction

Lightweight sandwich structures can offer greater structural performance than their monolithic counterparts under certain loading scenarios, e.g. their high bending strength to weight ratio can yield great weight-saving benefits for structural elements under bending and shear [1]. There has been an increasing interest in the application of sandwich structures for impact protection or blast mitigation [2,3]. Compared to a monolithic panel of equal areal mass, sandwich panels can offer a two-fold approach for increasing resistance to frontal shock loading, i.e. (i) increased flexural strength and (ii) a reduction of the transmitted shock impulse into the structure via the fluid-structure interaction (FSI) effects [4]. The effect of fluid-structure interaction is significant for water blast but relatively unimportant for air blast.

Development of high performance blast resistant sandwich structures has been mainly based on two types of sandwich core topologies, i.e. foam cores and periodic cellular cores. Inexpensive metallic or polymeric foams with stochastic closed cells are relatively easy for manufacturing [5,6] and prove to be excellent at absorbing energy during impact events [5]. However, their stochastic nature leads to curves and undulations within the cell walls, reducing their compressive properties [7]. It has been demonstrated that the deformation mode of the microstructure of stochastic foams is "bending-dominated" under macroscopic stresses [8,9]. This leads to the stiffness and strength scaling with $\bar{\rho}^2$ and $\bar{\rho}^{1.5}$, respectively, with $\bar{\rho}$ as the relative density of the foams [5]. Periodic cellular cores include those with two dimensional (2D) microstructures, such as honeycombs and corrugated cores as well as those with three dimensional (3D) microstructures, such as truss lattices. Truss lattices can be arranged with a tetrahedral, pyramidal or Kagome topology at the length scale of 0.5 to 15 mm. They can offer superior peak strengths at low relative densities [10,11]. They have been shown to exhibit 'stretch-dominated' deformation mechanism that provides about 10 times enhanced stiffness when compared with that of stochastic foams [12]. With less complexity in manufacturing compared to truss lattices, honeycombs and corrugated cores can offer good performance for blast protection owing to high compressive and transverse shear strengths [4,13].

Existing research have mainly focused on metallic sandwich structures [14], and have recently moved to composite sandwich structures, e.g. E-glass composite corrugated cores by Russell et al. [15] using stitching technique, and carbon fibre epoxy square

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honeycomb cores by Russell et al. [16] using slotted composite sheet methodology. The inherent high stiffness and strength and low density of fibre reinforced composite materials mean that they are ideally suited for use in lightweight sandwich panel design. Recent investigation has demonstrated the scenarios that fibre reinforced composite structures can outperform metallic structures under shock loadings [17]. However, due to their brittle nature and relatively complicated manufacturing processes, the design of an efficient composite structural sandwich panel system can prove difficult. This paper presents a novel solution using wrapped composite corrugated cores of low relative density for potential use of protection against dynamic compressive loading. In Section 2, it begins with a description of the material and the manufacturing technique employed for the creation of laboratory scale wrapped carbon-fibre composite cores. In Section 3, the experimental protocols for both quasi-static tests and dynamic compressive test are described. The quasi-static responses of the constitutive composite material and the wrapped cores are presented. In Section 4, the dynamic compressive responses of both the constitutive composite material and the wrapped cores are investigated utilising a direct impact Kolsky bar experiment.

2. Materials and manufacturing

Wrapped composite sandwich cores were manufactured using MTM57-T700 unidirectional carbon fibre/epoxy resin Pre-preg supplied by Cytec Solvay Group. The Pre-preg was made of Toray T700 fibre with diameter 7 μm and toughened epoxy resin with 35% fibre fraction by weight. Each layer of the composite material had a thickness of approximately 0.70 mm, a density $\rho_c = 1.22\ \mathrm{g/cm^3}$ and a Poisson's ratio $\nu = 0.3$ after cure.

The manufacturing process of the sandwich plate is schematically shown in Fig. 1. Powder based, destructible triangular prisms of base width $\lambda = 30$ mm and height $h = 15$ mm, acting as the internal mould, were manufactured using a rapid prototyping (RP) technique. The prisms were wrapped with PET based release tapes to allow for ease of demoulding post curing. Single layered pre-impregnated laminate tapes were then wrapped around each prism with an approximate overlap of each layer of 15 mm, located at the base of the isosceles triangle (Fig. 1(b)). The wrapped moulds were then arranged edge to edge, shown in Fig. 1(c), to create a full sandwich cores. Standard vacuum bagging technique was then employed for composite curing at atmospheric pressure. A Quicklock Thermoclave autoclave heated the plate for 3 h at 120 °C to facilitate curing (Fig. 1(d)). UD-laminate facesheets were then adhered to the top and bottom surfaces of the cores using Loctite Hysol© 9461 A&B epoxy adhesive of 1:1 mixture ratio. The facesheets consisted of 4 stacked plies in $[0/90]_2$ configuration giving a total thickness of 2.8 mm. The sandwich plate was clamped with a constant pressure at room temperature for 3 days to acquire full adhesive strength for the interfaces between the facesheets and the corrugated core (Fig. 1(e)). The fibre orientation of both the corrugated core webs and facesheets is shown in Fig. 1(e) under local 1-2-3 coordinate systems with 1-axis aligned with fibre direction. A sandwich beam after completion is shown in Fig. 1(f). The geometry of a representative unit cell of the corrugated core sandwich plate after cure is shown in Fig. 2 under the global x-y-z coordinate system, with base length $L = 30$ mm and height $h = 15$ mm, core web thickness $t_c = 1.4$ mm. The relative density of the corrugated core, defined as the ratio of the core density and the base material density, is 0.13. In compressive testing described next, individual corrugated core specimen were cut from the sandwich plate.

3. Experimental protocols

3.1. Tensile coupon test on the base material

Quasi-static (2 mm/min) uniaxial tension material coupon tests were conducted on the base composite material in order to determine the in-plane mechanical properties. A screw-driven Instron© 5581 type testing machine with a static 50kN load cell was utilised for testing. For tensile tests, dog bone shaped samples were employed following EN ISO 527-4 test method. The dog bone samples had width of 10 mm and a gauge length of 50 mm. The axial nominal strain was measured using an Instron 2630 series clip-on extensometer and confirmed using a single Stingray© F-146B Firewire Camera video gauge with post processing software Imetrum Video Gauge©. The load was measured directly from the test machine crosshead. The clip-on extensometer was removed prior to failure of the sample. Samples were tested with fibres orientated

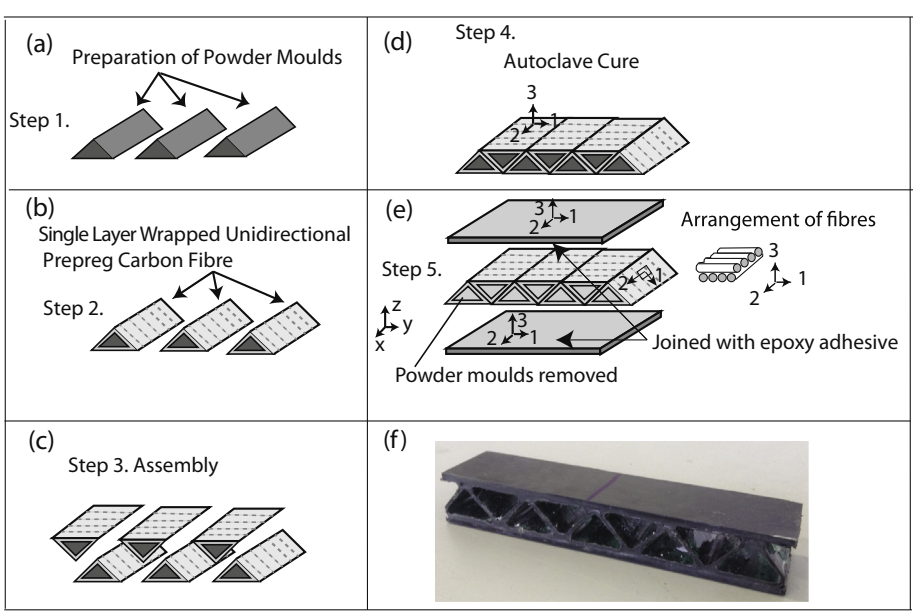

Fig. 1. The 5–step process to manufacture the composite sandwich structure with corrugated core [(a) – (e)] and an example sandwich beam after completion (f). The local coordinate system 1-2-3 is shown in the figure with axis-1 aligned with fibre direction on surface layers.

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