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Wavy-ply sandwich with composite skins and crushable core for ductility and energy absorption

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A B S T R A C T

Conventional composite materials offer high specific stiffness and strength, but suffer from low failure strains and failure without warning. This work proposes a new design for sandwich structures with symmetrically-wavy composite skins and a crushable foam core, aiming to achieve large strains (due to unfolding of the skins) and energy absorption (due to crushing of the foam core) under tensile loading. The structure is designed by a combination of analytical modelling and finite element simulations, and the concept is demonstrated experimentally. When loaded under quasi-static tension, wavy-ply sandwich specimens with carbon–epoxy skins and optimised geometry exhibited an average failure strain of 8.6%, a specific energy dissipated of 9.4 kJ/kg, and ultimate strength of 1570 MPa. The scope for further developing the wavy-ply sandwich concept and potential applications requiring large deformations and energy absorption are discussed.

1. Introduction

Fibre-Reinforced Polymers (FRPs) are remarkably stiff, strong and light materials, which makes them advantageous for lightweight structural applications. However, FRPs present a restricted ability to deform and withstand damage before catastrophic failure, which limits their applicability in damage tolerant components. This paper proposes a wavy-ply sandwich structure to generate significant ductility and energy absorption in FRPs.

Increasing the ductility of composites requires engineering extra deformation mechanisms, since most technical fibres (e.g. carbon and glass) have low extensions at failure. One possibility is to use fibre waviness to provide excess length and allow for further extensions due to fibre re-orientation during loading [1–3]. This requires tailoring the response of the matrix, which should be sufficiently stiff to provide initial resistance to fibre rotation, but flexible enough to accommodate large deformations due to fibre unfolding at higher loads. This concept has been explored by using waviness at the fibre level [1,2] or corrugated plies [3].

Increasing the energy absorption of composites requires introducing mechanisms to spread the damage and avoid localised failure. A typical solution is to use sandwich structures, where the composite skins provide stiffness and strength, and a light crushable core dissipates damage and energy. Sandwich structures used under crushing [4,5] or bending [6,7] show greater specific energy absorptions than the monolithic counterparts.

These strategies can be combined into sandwich materials with wavy skins. Several authors [8–11] analysed asymmetric sandwich structures composed by one straight skin, one wavy skin with periodic profile, and a matching machined foam core. Under tension, the straight skin would initially carry the load until first fracture within one of the periodic cells; the wavy skin would then unfold and stretch locally, transferring the load back to the remaining straight segments at stitched points. This process would be repeated until the straight skin was fractured in all periodic cells, and the wavy skin was fully stretched.

Such asymmetric sandwich structures [8–11] achieved larger failure strains and specific work of fracture than the corresponding monolithic materials. However, most energy was dissipated unstably, with significant load drops following each fracture event of the straight skin. Moreover, the foam core was used simply to define the wavy profile, and its potential to absorb energy was not explored.

These drawbacks suggest that the potential of wavy-ply sandwich structures for large deformations and energy absorption has not been fully exploited yet. This work proposes a sandwich structure with symmetric wavy skins and a crushable core, aiming to combine (i) large deformations (through fibre re-orientation), (ii) energy absorption (through crushing of the core), and (iii) a stable non-linear tensile response (with no significant load drops).

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The new wavy-ply sandwich concept [12] is illustrated in Fig. 1 and further described in Section 2. The sandwich structure is designed in Section 3, using a combination of analytical and Finite Element (FE) modelling. Section 4 describes the manufacturing and testing of wavy-ply sandwich specimens, and the results from the experimental characterisation are detailed in Section 5. The potential of the proposed concept is discussed in Section 6, and the main conclusions are summarised in Section 7.

2. Concept and materials

The wavy-ply sandwich concept [12] is designed for in-plane tensile loading (see Fig. 1) and relies on the following three components:

- *Wavy skins*: the skins are the main load-carrying element. Their initial waviness will provide excess length during tensile loading, allowing for large remote extensions through unfolding. The skins will be manufactured with a Carbon-Fibre Reinforced-Polymer (CFRP) with toughened epoxy matrix (Hexcel M21/35%/198/T800S [13–16]).
- *Crushable core*: while the core should provide initial stiffness to the system, it will allow the wavy skins to unfold with further loading and absorb energy through crushing. The crushable core cells will be machined from EVONIK ROHACELL RIMA foam (high-performance closed-cell PMI-based foams, specifically developed for minimal resin absorption) [17], and bonded in situ during the cure of the CFRP skins.
- *Bridging region*: the bridging region (where the two skins are bonded together) will experience opening stresses due to the initial stiffness of the core, with large stress concentrations at the edges of the core cells. Fillets of resin (made from Hexcel M21 film [13]) will therefore be used to prevent delamination (see Fig. 2).

Properties of the materials are provided in Tables 1–5. The next section will define the remaining design variables of the concept (see Fig. 2).

Table 1
Geometric and mass properties of the M21 matrix (superscript m) and M21/35%/198/T800S CFRP plies (superscript p) [13].

t^{m} (mm)	ρ^{m} (g/cm^3)	w^{m} (g/m^2)	t^{p} (mm)	ρ^{p} (g/cm^3)	w^{p} (g/m^2)
0.027	1.28	35	0.193	1.58	305

3. Modelling and design

3.1. Analytical modelling and wave geometry design

3.1.1. Model development

The strength and maximum extension of the wavy-ply sandwich structure under remote tension can be estimated through the analysis of the wavy skins (of thickness t^{w}) under bending coupled with tension, neglecting the presence of the (by then failed) foam.

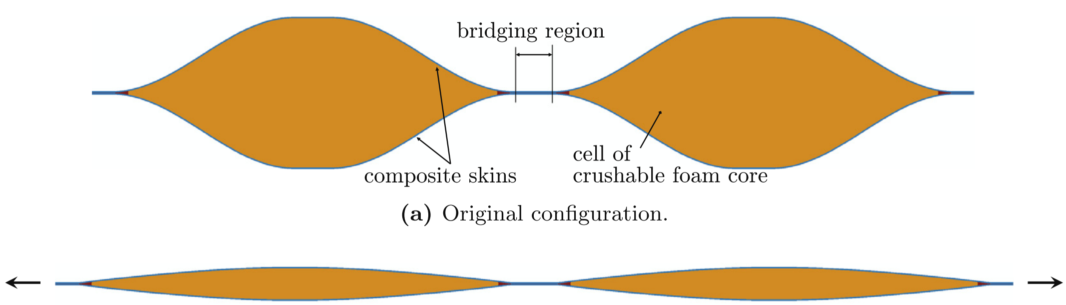
Consider the sinusoidal profile $y(x)$ represented in Fig. 2; this is characterised by the half-length L^{w} and half-amplitude A^{w}, so that the aspect ratio is $\alpha = A^{w}/L^{w}$ and:

$$y(x) = \alpha \cdot L^{w} \cdot \sin\frac{\pi \cdot x}{L^{w}}, \quad \text{hence} \quad \begin{cases} \frac{dy}{dx} = \alpha \cdot \pi \cdot \cos\frac{\pi \cdot x}{L^{w}} \\ \frac{d^2y}{dx^2} = -\frac{\alpha \cdot \pi^2}{L^{w}} \cdot \sin\frac{\pi \cdot x}{L^{w}}. \end{cases} \tag{1}$$

Let X_{∞} and e_{∞} be respectively the remote strength (normalised by the thickness of the composite skins, $2 \cdot t^{w}$) and failure strain of the wavy-ply structure. Failure will ideally occur when the wavy skins are completely flattened (i.e. the foam core is completely crushed and the deflection is $v(x) = -y(x)$), under the combination of remote tensile stresses (X_{∞}) and maximum bending stresses (σ_{B}^{max}). If E_{T1}^{p} and X_{T1}^{p} are respectively the stiffness and strength of the composite plies in longitudinal tension, then X_{∞} must satisfy:

$$X_{T1}^{p} = X_{\infty} + \sigma_{B}^{max}, \quad \text{with} \quad \sigma_{B}^{max} = \frac{t^{w}}{2} \cdot \left.\frac{d^2y}{dx^2}\right|^{max} \cdot E_{T1}^{p}. \tag{2a}$$

The overall strain will have contributions from the extension and the unfolding of the skins. If s^{w} is the half-wave arc-length, then e_{∞} will be:



(a) Original configuration.

(b) Deformed configuration.

Fig. 1. Wavy-ply sandwich concept.

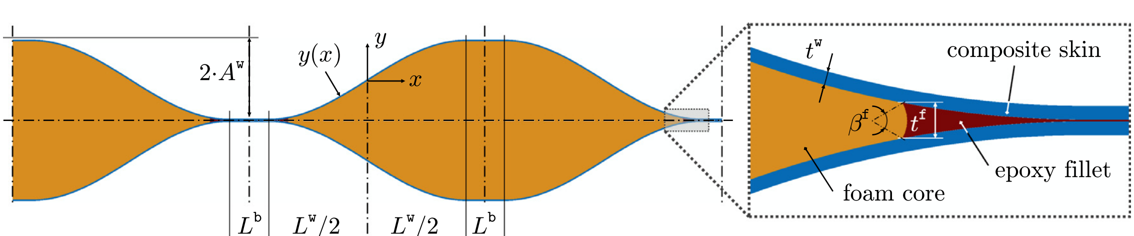


Fig. 2. Geometry of the wavy-ply sandwich structure, highlighting the design variables to be defined through modelling: (i) geometry of the wavy profile, (ii) geometry of the bridging region, and (iii) density of the foam for the crushable core.