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Prediction and experiment on the compressive property of the sandwich structure with a chevron carbon-fibre-reinforced composite folded core

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ABSTRACT

The compressive performances of carbon-fibre-reinforced composite sandwich panels with chevron folded cores were investigated in this paper. Analytical expression based on energy approach were derived to predict their compressive elastic modulus and strength. The sandwich panels with specific fibre orientation cores were manufactured and tested to reveal the influences of fibre ply angles on the responses for compressive loading. The stiffness and strength increased distinctly with the 0° fibre orientation increments. The predictions for compressive stiffness and strength showed good agreement with the measurements, and the failure mechanisms of the structures were discussed by simulation analysis.

1. Introduction

Traditionally, composites plates with stringers were used in the aircraft manufacture, while the massive and complex stringer structures usually reduce the performance of overall carrying structure. Therefore, sandwich panels are widespread in modern industry for their well-known structural efficiency such as energy absorption properties [1]. They are made of a light core which is connected between two stiff faces. Recently, scientists focus on types of cores such as foam and lattice truss [2] for various practical conditions. Core design consists in maximizing its mechanical properties and weight efficiency. *Honeycomb sandwich structures are considered as a representatively efficient cellular core geometries due to their specific bending resistance performance and absorption energy capability. However, they have some drawbacks. The iterative fabrication process makes it an expensive material. Furthermore, the closed-cell structural feature would lead to the accumulation of humidity in the practical application, which can damage the bound between cores and skins and also cause unexpected delamination* [3]. Thus, the field of applications of honeycomb structures is limited to the secondary carrying structures, such as fairing, door, control surfaces and cabin paneling of an aircraft. In order to realize the utilization of sandwich panels in fuselage shell, folded cores attracted the attention from the industry.

The folded core origins from Origami, which is manufactured by folding a planar base material into a three-dimensional structure. The Miura-Ori pattern has one-degree of freedom and can be folded or unfolded without deforming the base material [4]. An advantage of folded cores is the open cellular design, which allows ventilation through the open channel, thus the problem of moisture accumulation can be solved [5]; [6]. Moreover, the folded core structure has high stiffness and strength to weight ratios [6]; [7]. The structure can be manufactured out of a large variety of base materials: papers, carboard, metals(aluminum, steel, titanium) [8], advanced fibre reinforced materials (glass, carbon, aramid fibres) [9] as well as different thermoplastic films (PC, PVC, PPSU, PEEK) [10]; [11]. Therefore, a surge in research interests was driven by the aerospace industry. For example, the project CLEPACT in the EU evaluated the fabrication cost and impact performance of folded cores [12].

A large amount of experimental work and numerical simulations were performed to investigate the mechanical behavior of folded cores. Heimbs et al. analyzed [8] [13]; the mechanical properties of carbon and aramid folded cores under quasi-static compressive loads, and characterized them by a ductile behavior. Hampf [14] investigated two-phase energy absorption behavior of a

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dual-core configuration with two folded cores, and evaluated the damage patterns and energy absorption mechanisms. Baranger [15] gave basic key points, including defects, to have a predictive modelling of the behavior of aramid folded under compaction. In order to describe out-of-plane compressive behavior of wedge-shaped folded cores [16]; [17], chevron folded cores and tapered cores, finite element models were developed with LS-DYNA. Tolman [18] [19]; investigated elastic energy absorbing properties and force distribution of the structures and explored the effects of key geometric parameters of the tessellation using analytical models. Zhou [20] presented a parametric study on the mechanical properties of a variety of Miura-based folded cores virtually tested in quasi-static compression, shear and bending using the finite element method. Hähnel [21] developed a procedure based on numerical methods to predict the structural response of wedge-shaped folded cores under compressive and shear loading. A. Lebée [22] did analytical research to predict the transverse shear stiffness of a chevron folded core and indicated that exist upper and lower bounds. Fan [23] equilised Kagome cores into I-shaped beams to calculate the bending stiffness of cylinder sandwich structure and studied the vibration characteristics. Liu [24] analytical predicted the bending failure loads of pyramidal truss cores. However, rare papers concerned the analytical prediction for carbon-fibre folded core sandwich structure under compressive loads.

In the present study, the compressive characteristics of carbon-fibre composite chevron folded sandwich panels were investigated. The analytical models based on energy approach were proposed to estimate the compressive stiffness and strength of the structures in Section 2. Flatwise compressive experiments were performed to determine the constitutive models, and the influences of different orientations fibres on the compressive property were investigated in Section3 and Section 4, the failure mechanism of the structure was revealed via finite element method. Finally, the conclusion was drawn.

2. Analytical models

2.1. Assumptions and preliminary definitions

Following basic assumptions are defined to simplify the equations and calculations:

(1) Perfect combination is assumed to the skins and the folded cores. There are no defects inside;
(2) Only in-plane stresses are considered in the thin parallelogram facets;
(3) The compressive behavior is based on linear elastic small deformation analysis.

In this paper, to facilitate theoretical deducting and trying to maintain the geometrical characteristic of the unit cell, a simplified configuration constituting with four equal parallelogram facets is illustrated in Fig. 1. The geometric parameters α, β, a, b fully determine geometry of the cell. As for this topological configuration, φ and α, β have the relationships follows:

$$\begin{aligned} \cos\varphi &= \cos\alpha \cdot \cos\beta \\ \sin^2\varphi &= \sin^2\alpha + \cos^2\alpha \cdot \sin^2\beta \end{aligned} \tag{1}$$

2.2. Conversion coefficients

Due to the structural symmetry, stress state in facet ABCD is only

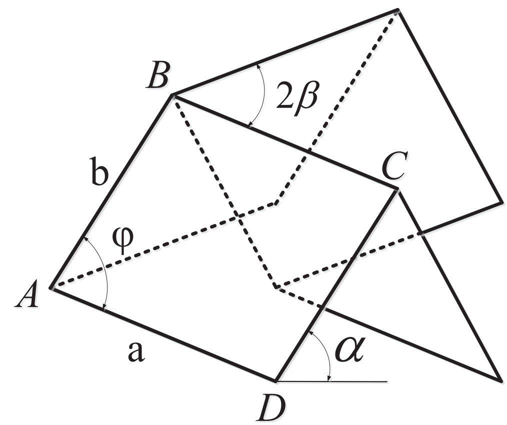

Fig. 1. A geometrical model of the unit cell.

going to be analyzed. As shown in Fig. 2(a), the facet is placed in the global coordinate system xyz, base vectors for which are $e_i (i = 1, 2, 3)$. In Fig. 2(b), in-plane stress directions and the local coordinate system of the facet are given. g_i can be made to coincide with e_i through either a rigid body rotation. Namely, they can be related by an orthogonal tensor through the equations:

$$\mathbf{g}_i = \boldsymbol{\beta}_i^{j'} \mathbf{e}_{j'} \tag{2}$$

where, $\boldsymbol{\beta}_i^{j'}$ is the covariant conversion coefficients of the reciprocal basis satisfying the condition:

$$\boldsymbol{\beta}_k^{j'} \cdot \boldsymbol{\beta}_{i'}^{k} = \delta_{i'}^{j'} \tag{3}$$

The transformation law relating the strain components $\varepsilon_{k'l'} (k', l' = x, y, z)$ in the global coordinate system and $\varepsilon_{kl} (k, l = 1, 2)$ in the local coordinate system $\xi' o \eta'$ satisfy coordinate are defined as:

$$\varepsilon_{kl} = \beta_k^{k'} \beta_l^{l'} \varepsilon_{k'l'} \quad (k', l' = x, y, z, \; k, l = 1, 2, 3) \tag{4}$$

2.3. Equivalent elasticity coefficients

As shown in Fig. 3, $E^{i'j'k'l'}$ has a clear physical meaning in the rectangular coordinate system, basis vectors of which are $\mathbf{e}_i (i = 1, 2)$. In the oblique coordinate system $\xi' o \eta'$, elasticity coefficient E^{ijkl} can be described by elasticity coefficient $E^{i'j'k'l'}$ of laminates.

The transformation law relating the stress components σ^{ij} in the oblique coordinate system$\xi' o \eta'$ and $\sigma^{i'j'}$ in the rectangular coordinate system are defined as:

$$\sigma^{ij} = \beta_{i'}^{i} \beta_{j'}^{j} \sigma^{i'j'} \tag{5}$$

In the same way, the transformation law for strain components are expressed:

$$\varepsilon_{k'l'} = \beta_{k'}^{k} \beta_{l'}^{l} \varepsilon_{kl} \tag{6}$$

According to the constitutive relation of laminate theory, the uniformly distribute in-plane stresses σ^{11}, σ^{22}, σ^{12} of the parallelogram laminated wall (facet ABCD) in the rectangular coordinate system can be described as:

$$\sigma^{ij} = E^{ijkl} \varepsilon_{kl} \tag{7}$$