



Failure mechanisms of sandwich composites with orthotropic integrated woven corrugated cores: Experiments

Fengnian Jin^b, Hailong Chen^b, Long Zhao^{b,c}, Hualin Fan^{a,d,*}, Chuanguo Cai^b, Ning Kuang^e

^a Laboratory of Structural Analysis for Defense Engineering and Equipment, College of Mechanics and Materials, Hohai University, Nanjing 210098, China

^b State Key Laboratory for Disaster Prevention & Mitigation of Explosion & Impact, PLA University of Science and Technology, Nanjing 210007, China

^c State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China

^d State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China

^e Nanjing Fiberglass Research & Design Institute, Sinoma Science & Technology Co. Ltd., Nanjing 210012, China

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ABSTRACT

To enhance the skin–core debonding resistance of sandwich composites, a new integrated woven corrugated sandwich composite (IWCSC) was designed and fabricated. Quasi-static compression, shearing and three-point bending tests were carried out to reveal the mechanical property and the failure mechanism of the IWCSC. In compression, gradual core crushing and contacting with the skin induced ductile load–displacement curves featured by a long deformation plateau. The anisotropic core structure leads to orthotropic anti-shearing resistances in the warp and weft directions. The difference is even at the level of a magnitude. IWCSC is an anisotropic bending dominated light weight material. Anisotropy of the core structure leads to different failure mechanisms of IWCSC panels in bending. Bended in the warp direction failure mode of the beam is core shearing while in the weft direction is indentation. High skin–core debonding resistance has been testified by the experiments. Behaviors of IWCSC panels were predicted and the predictions are close to the tested data.

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1. Introduction

Composite sandwich materials with honeycombs, foams, web stiffeners and other cores [1] are currently under rapid development for lightweight panel and beam components in aircrafts, space structures, vehicles and civil engineering structures [1–4]. Compared with other sandwich structures, sandwich panels consisting of integrated woven cores provide sandwich materials high skin–core debonding resistance. Fan et al. [5–9] designed and made different integrated woven lattice panels and revealed their failure mechanisms and excellent energy absorption abilities. Brandt et al. [10] reviewed the mechanical performances of various three-dimensional woven composites by comparisons of in-plane properties (stiffness and strength), damage tolerance, energy absorption capability and fracture mechanical properties. Vuure et al. [11–13] studied the strength and stiffness of the material by experiments and numerical simulations. Investigations [14,15] were also conducted for other properties, such as fatigue, damage, and low velocity impact responses. To enhance the skin, Shiah et al. [16] used the woven textile fabrics as the core which was co-cured

with laminated plastic-layers to form integrated sandwich composites. All these structures have integrated woven cores resembling 8 shapes. Johnson et al. [17] developed a box-section cellular structure consisting of a pair of woven fiber/epoxy skins, separated by braided glass fiber/epoxy cores of square sections.

Such woven materials are suitable for low-cost and automated productions. In this paper, mechanical performances of a woven textile material with orthotropic integrated woven corrugated cores were revealed by quasi-static experiments.

2. Manufactures

Integrated woven corrugated sandwich composite (IWCSC) was designed and fabricated by Nanjing Fiberglass Research & Design Institute. As shown in Fig. 1, the textile consists of an upper skin, a lower skin and a corrugated core. The skins are woven by two body warp yarns and side weft yarns. The corrugated core is woven by two warp yarns and weft yarns. At each joint, the skin and the core are integrated by a co-shared weft yarn.

The woven textile has a sandwich structure as shown in Fig. 2a. The wave-like walls form the corrugated core while the ultra-thin faces are attached to thick laminates and then co-cured to form the integrated sandwich composite as shown in Fig. 2b. IWCSC sample is shown in Fig. 2c. The core structure resembles a wave shape in the warp direction and a continuous plate in the weft direction.

* Corresponding author at: Laboratory of Structural Analysis for Defense Engineering and Equipment, College of Mechanics and Materials, Hohai University, Nanjing 210098, China.

E-mail address: fhl02@mails.tsinghua.edu.cn (H. Fan).

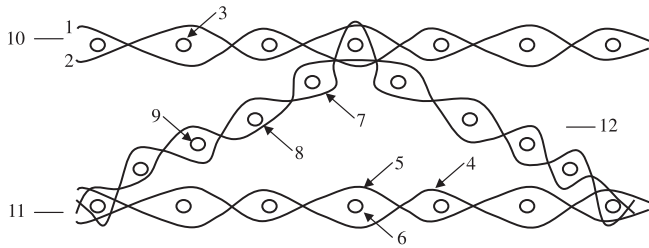


Fig. 1. 3D woven method of IWCS textile, consisting of the upper skin (10), woven by (1) body warp, (2) body warp and (3) side weft yarn, the lower skin (11), woven by (4) body warp, (5) body warp and (6) side weft yarn, and the corrugated core (12) woven by (7) core warp yarn, (8) core warp yarn and (9) core weft yarn.

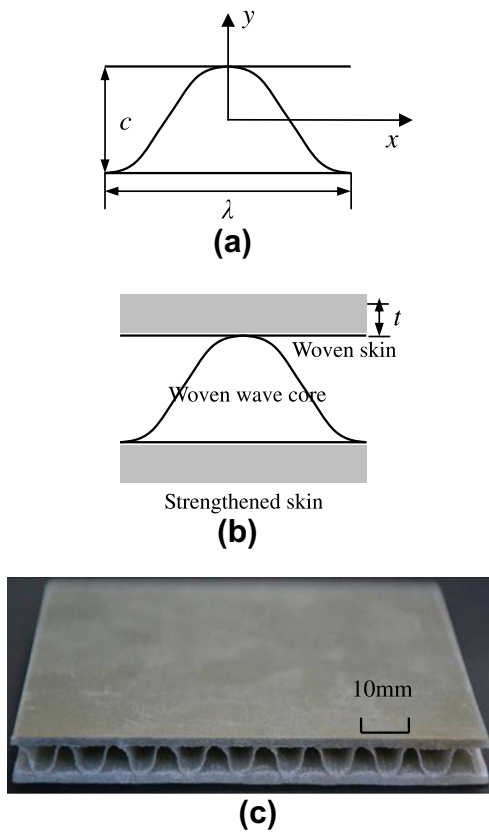


Fig. 2. Warp structure of (a) integrated woven sandwich composite with ultra-thin sheets and wave cores, (b) sandwich panel with strengthened skins, and (c) finished sample.

Different cellular structures in the warp and weft directions lead to orthotropic mechanical performances for the sandwich composite in in-plane compression, shearing and three-point-bending experiments.

Ideally corrugated core material should be made up of triangular trusses with straight struts. Strength and stiffness of such truss core material would be proportional to its relative density. In fact, the woven core has a wave shape, as shown in Fig. 1a. Length, L , and width, b , of each compressed sample are 100 mm, respectively. Thickness of the skin, t , is 2 mm. Thickness of the woven core, c , is 4 mm. Thickness of the sample is 8 mm. Periodic wave length of the corrugated core, λ , is 10.2 mm. Thickness of the wall of the corrugated core, t_c , is about 0.4 mm. Relative density of the core, ρ^* , is about 0.16. Mechanical properties of IWCS, related to the relative density and physical properties of the woven core, were revealed by experiments and predicted by simplified equations.

3. Failure modes in compression

3.1. Out-of-plane compression

Compression experiments at a rate of 0.2 mm/min were carried out on DNS 300 test machine. In tests, displacements were directly measured by the test machine. Loading was controlled by the closed-loop control of the displacement, whose precision accuracy is controlled within $\pm 0.5\%$. As shown in Fig. 3, the load-displacement curves exhibit four characteristic stages, namely elastic deformation, buckling softening, deformation plateau, and densification. In the elastic stage, the wave wall in the core was compressed accompanying with bending deformation, as shown in Fig. 4. Nominal strength of the woven core is about 1.1 MPa in average, varying from 0.9 to 1.5 MPa. Elastic stiffness is about 15.9 MPa, varying from 11.8 MPa to 18 MPa. When loaded to the peak value, buckling of the wall leads to an abrupt load drop. As shown in Fig. 3, damages and ruptures of the core are originated from the joints. The damage part of the wave then will be compressed and attach to the skin. The sandwich core will be gradually thinner and the wave wall gets steeper, keeping a relatively strong anti-crushing resistance. Stress of the deformation plateau keeps at the level of 0.5 MPa, nearly a half of the peak stress.

It is revealed that the flexible wave core is apt to buckle in compression. Strength and stiffness of IWCS have few advantages compared with other woven textile sandwich composites [7,8]. But the gradual damage and contacting behaviors make the material have a relatively stable deformation plateau and a ductile failure mode.

3.2. In-plane compression

In-plane compressions were carried out to get the mechanical behaviors of the skin panels. Height of the compressed panel is only 10 mm to avoid integral instability. Length of the sample is 60 mm. Compressed in the warp direction, the laminate skin has an average strength of 52.6 MPa and an average stiffness of 575.3 MPa, as shown in Fig. 5. The compression strength in the weft direction is 61.2 MPa, 16.3% higher than the compression strength in the warp direction, consistent with the fraction of the volume of the core material to the volume of the skins, which is about 0.16. Average stiffness in the weft direction is 737 MPa, 28% higher than the compression stiffness in the warp direction.

It is concluded that the core material should have important contributions to the anti-compression ability in the weft direction, while this effect would be neglected in the warp direction.

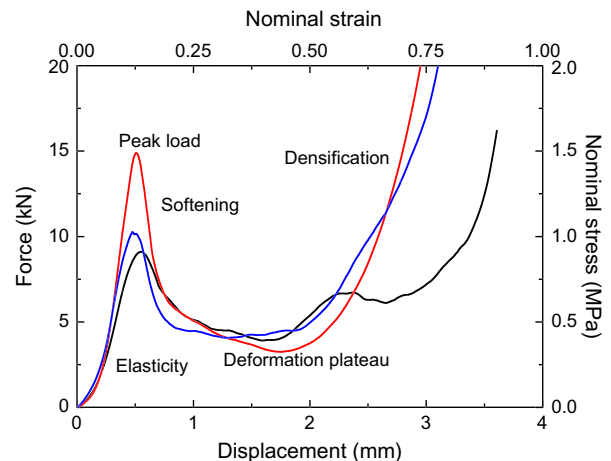


Fig. 3. Compression curves of IWWSC panels.

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