Composites Science and Technology 72 (2012) 1338–1343

Contents lists available at SciVerse ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Ductile deformation mechanisms and designing instructions for integrated woven textile sandwich composites

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ARTICLE INFO

Article history:
Received 22 October 2011
Received in revised form 20 April 2012
Accepted 28 April 2012
Available online 17 May 2012

Keywords:
A. Textile composites
B. Mechanical properties
B. Stress/strain curves
C. Deformation
C. Modelling

ABSTRACT

To suggest designing instructions for integrated woven textile sandwich composites (IWTSCs), anti-crush properties of IWTSC and the corresponding ductile deformation mechanism were investigated. Quasi-static out-of-plane crushing and dynamic impact tests were carried out. Typical deformation curves with a relative stable deformation plateau were obtained from tests. Failure of IWTSC is ductile through coupled compression–shear deformation. An analytical plastic model was proposed to explain ductile mechanism of IWTSC qualitatively, including densification caused by interactions among inclined piles. Combining with qualitative analysis, comparisons between two kinds of IWTSC panels with piles of different density and thickness reveal the key to design a ductile IWTSC.

1. Introduction

Integrated woven textile sandwich composite (IWTSC) is a lightweight sandwich structure with integrated skins and core piles [1–4] as shown in Fig. 1. Topology of the core piles does not agree with the stretching dominated principle for lattice truss composite (LTC) [5,6]. Vuure et al. [1] have proposed a special finite-element preprocessing program based on a detailed model of the pile and pillar shapes and the resin distribution to model the linear static core properties of IWTSC panels. They did not explain the ductile mechanism of IWTSC. It seems that IWTSC would not be so weight efficient and attractive as LTC for light structures. But large scale textile weaving process greatly reduces the manufacturing cost. Furthermore, IWTSC displays ductile deformation mechanism in compression [7] and dynamic impact while LTC is brittle [6,8,9].

In China, weaving technology of IWTSC has been developed by Nanjing Fiberglass Research and Design Institute (NFRDI) and other several enterprises. Based on IWTSC, Fan et al. developed multilayered sandwich panels [10] and hierarchical lattice composites [11]. These hierarchical structures are ductile and have excellent energy absorbing abilities. IWTSC has also been applied in vehicles. A new IWTSC wind deflector structure for China Railway High-speed (CRH) trains has been fabricated by NFRDI as shown in Fig. 2. Originally, the wind deflector structure is made of glass fiber reinforced laminates. Made of IWTSC, more than 50% mass of the wind deflector is reduced. Applied in high speed train bodies, IWTSC must meet out-of-plane anti-crush and anti-penetration requirements due to high-speed wind pressures and accidental impacts.

Out-of-plane crushing responses of IWTSC were researched in this paper. A qualitative analytical model would be suggested to explain the ductile deformation mechanism of IWTSC.

2. Experiments

2.1. Quasi-static compressions

Samples supplied by NFRDI are woven by glass fibers and solidified by ethoxyline resins. Length and width of each sample are 100 mm, respectively. Thickness of the samples is 10.5 mm. The sandwich skins are about 1.0 mm and 2.0 mm thick. Distance between neighboring piles is 6.7 mm. Piles in the core has a thickness of about 3.0 mm. The density is about 3000 g/m^2.

Quasi-static compression experiments at a rate of 1 mm/min were carried out on DNS 300 machine. Deformation curve and failure mode were shown in Figs. 3 and 4, respectively. Three stages were found in the load–displacement curves [7], including elastic

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http://dx.doi.org/10.1016/j.compscitech.2012.04.017

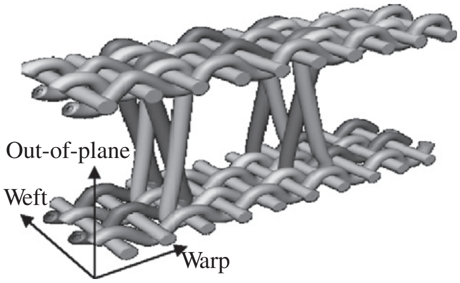

Fig. 1. Typical IWTSC wove structure.

Fig. 2. Application of IWTSC in wind deflector of CRH trains.

deformation, compression–shear coupling failure plateau and densification as shown in Fig. 5. Samples have an average strength of 4.4 MPa, varying from 3.8 MPa to 5.5 MPa. Scattering of the strength comes from the control error of the woven geometry and hand lay-up and curing process at room temperature. Before the peak load, piles will be compressed and the deformation of IWTSC is in elastic stage. Development of pile inclination in this stage is not obvious. After the peak load, piles began to incline companying with dropping load. Compression–shear coupling failure leads to a softening deformation plateau. Further compression makes inclined piles contact with each other companying with load rising up. When unloaded, springback of piles was observed in the testes. Deformation of the woven textile sandwich is ductile.

2.2. Dynamic compressions

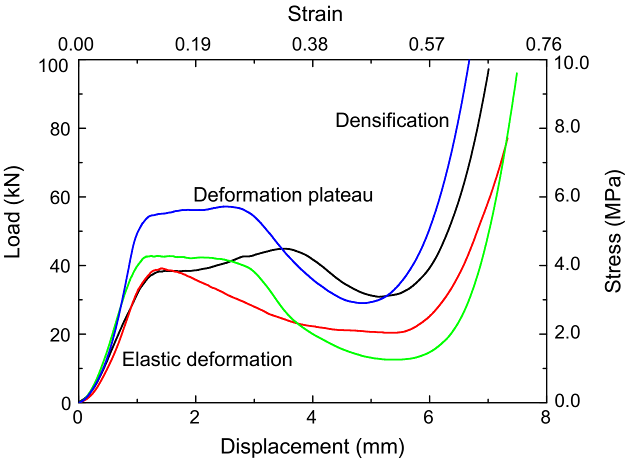

Fig. 3. Quasi-static compression curve of IWTSC.

Fig. 4. Crushed and intact woven geometry of IWTSC in quasi-static compression.

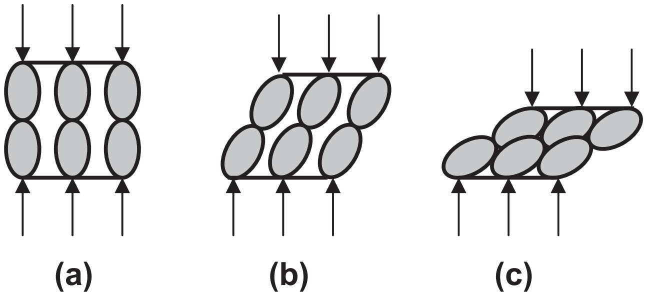

Fig. 5. Deformation of piles during compression in (a) elastic deformation, (b) compression–shear coupling failure and (c) interaction and densification.

Dynamic compression experiment was carried out on DYNATUP 9250 HV machine in MOE Key Lab of Disaster Forecast and Control in Engineering. To change the mass of the hammer and the velocity, the tests were divided into three operating cases. In case I, the mass of the hammer is 49.57 kg and the impact velocity is 2.7 m/s. So the impact energy is 180 J. In case II, the mass of the hammer is 49.57 kg and the impact velocity is 3.8 m/s. So the impact energy is 360 J. In case III, the mass of the hammer is 30.72 kg and the impact velocity is 3.4 m/s. So the impact energy is 180 J. Forces acted on IWTSC samples are measured by the gauge on the impactor. Velocity of the impactor is measured by optical encoder for precise crosshead positioning. Under these loading cases, initial equivalent loading rates for panels are 257.1 s^{-1}, 361.9 s^{-1} and 323.8 s^{-1}, respectively.

Tested dynamic force–displacement curves were shown in Fig. 6. In case I, samples have an average strength of 5.2 MPa, varying from 3.7 MPa to 7.0 MPa. In case II, samples have an average strength of 5.7 MPa, varying from 4.6 MPa to 6.2 MPa. In case III, samples have an average strength of 5.6 MPa, varying from 3.5 MPa to 7.7 MPa. Scattering of the strength also comes from the control error of the woven geometry and hand lay-up and curing process at room temperature. The dynamic strength is just a little larger than the static strength.

Consistent with the quasi-static curves, long deformation plateau featured the curves after yield or buckling. The crushing mechanism of the woven textile sandwich by coupled compression/shear was also observed in the low-velocity compression tests as shown in Fig. 7, which leads to a long deformation plateau after the peak buckling force. The plateau is much more stable compared with quasi-static compression curves. Accordingly, the woven textile sandwich panels have capability to absorb energy in shock and impact. Instead of densification, obvious springback was observed. Energies supplied by the impactor have been completely consumed before densification. The materials were not completely damaged.

Both quasi-static and dynamic curves reveal the ductile failure styles and the excellent energy absorbing abilities of IWTSC panels. Although in dynamic impact, woven panels have greater strengths and energy absorptions, they have similar ductile mechanism, including coupled compression/shear deformation, pile plastic rotation and springback.

3. Analysis

3.1. Elastic deformation

According to the experiments, a typical deformation curve of the woven panel three stages, including elastic deformation,