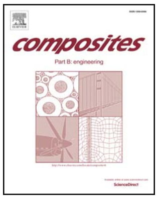
Composites Part B 142 (2018) 159–170

Contents lists available at ScienceDirect

Composites Part B

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



Multi-objective optimization for designing a composite sandwich structure under normal and 45° impact loadings

Yuan Chen[a], Kunkun Fu[a], Shujuan Hou[b], Xu Han[b], Lin Ye[a,*]

[a] Centre for Advanced Materials Technology (CAMT), School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha City 410082, PR China

ARTICLE INFO

Keywords:
Composite sandwich structure
Multi-objective optimization
Low-speed impact
Finite element analysis
Oblique impact

ABSTRACT

With their lightweight character and high energy absorption capacity, composite sandwich structures have attracted increasing attention in the transportation industry. The aim of this work is to present a new approach to investigate and optimize a composite sandwich structure by taking into account both normal and 45° low-speed impact loadings. First, a finite element model considering elastic-plastic, damage, and failure behaviours of the composites by using continuum damage mechanics is developed and validated by a normal low-speed impact test. Second, dynamic effects of normal and 45° impacts on energy absorption and failure behaviours of the composite sandwich structures are investigated. Then, a parametric study is performed to systematically understand the influences of core depth and cell thickness on the impact resistance of the sandwich composite structures subjected to both normal and 45° impacts. In contrast to their metal counterparts, it is interestingly found that absorbed energy generally increases with cell thickness, with a small extent of fluctuation, whereas core depth jumps, and the energy absorption capacity remains almost steady under normal impact but varies irregularly under the 45° impact. Afterwards, a multi-objective optimization is performed to enhance the energy absorption under both normal and 45° loadings. The energy absorption capability of the optimal composite sandwich structure can remarkably be improved by 12.447% for normal impact, and 7.9% for 45° impact. This method provides a new manner and systematic guidance for designing a lightweight composite sandwich structure more practical for engineering application.

1. Introduction

Composite sandwich structures have attracted increased attention in a number of engineering realms with regard to lightweight structural applications due to their high stiffness-to-weight ratio, energy absorption capability and high crashworthiness. In particular, composite sandwich structures with thin composite skins and honeycomb core are of great interest because, with this constituent structure it is easy to lighten weight effectively and, more importantly, this structure can be designed so as to protect passengers by lessening impact energy, whenever impacts crash into the skins at either a normal or an oblique angle. It is necessary, therefore, to be able to lighten the weight design of a composite sandwich structure with high energy absorption capacity under both normal and oblique impact loadings.

In recent decades, many researchers have experimentally investigated composite sandwich structures with a honeycomb core subjected to a low-speed normal impact load [1–7]. Further, numerical modelling techniques have gradually become an indispensable part of studying and designing composite sandwich structures, because such understanding can substantially reduce the number of trials and the resource costs. Hence, many publications have prioritised study of failure mechanisms and damage behaviour under low-speed impact using a numerical model [8–15]. While most existing studies have investigated composite sandwich structures under a normal impact load [16–18], studies on oblique impact behaviour of composite sandwich structures are rare, especially sandwiching with honeycomb core, even though certain differences in impact damage behaviours and significant changes in energy absorption are induced by obliquity.

To study the impacts associated with obliquity, certain investigations have been performed on metal tube or honeycomb structures [19–25] and metal sandwich structures within the high-speed scope [26–28]. For instance, Reyes et al. [19–21] performed a series of studies on the aluminum tubes under oblique impact using the numerical and experimental methods to study the dynamic responses and failure behaviours. Wang et al. [24] studied the deformation mode and evolution mechanism of aluminum honeycomb structure under oblique loadings. Zhou et al. [29] investigated perforations on sandwich panels containing monolithic stainless-steel sheets subjected to ballistic loading,

---

[*] Corresponding author.
E-mail addresses: shujuanhou@hnu.edu.cn (S. Hou), lin.ye@sydney.edu.au (L. Ye).

https://doi.org/10.1016/j.compositesb.2018.01.020
Received 26 December 2016; Received in revised form 25 November 2017; Accepted 21 January 2018
1359-8368/

and discussed the responses to a hemispherical projectile and a flat-nosed projectile under 45°–90° impact angles of obliquity. Ebrahimi et al. [30] performed a numerical study of the blast (shock) responses of metal square honeycomb sandwich panels subjected to projectile impact. Subsequently, they discussed the responses under the impact angles of 45° and 75°. In contrast, certain researches have been conducted for composite tube structures under oblique impact [31–34], but only a few studies have taken into account the effects of impact obliquity on composite sandwich structures. Chen et al. [35] studied the effects of impact obliquities on the dynamic responses and behaviours of the composite sandwich structures. Zhou et al. [36] studied the relationship between the perforation resistance of composite sandwich structures and the impact angle of obliquity. That work was followed by Ivañez et al. [6], who studied experimentally and numerically the damage response of composite sandwich honeycomb structures subjected to oblique impact at different angles and velocities, emphasizing that there were quite a few relevant materials in terms of low-speed oblique impact on composite material sandwich structures, worthy of further study.

In practice, it is indeed meaningful to optimize structures to meet engineering design requirements after acquiring their impact behaviours and responses. For example, Hou et al. [37] implemented an optimization study of metal hexagonal honeycomb panels using FE analysis (FEA) and a response surface method (RSM). Likewise, Fazilati et al. [38] employed FEA and the RSM to design and optimize a multilayer configuration of hexagonal metal honeycomb energy absorbers. Accordingly, many studies [39–41] have attached greater importance to the study and design of metal honeycomb sandwich structures under quasi-static or dynamic compression. This situation is more or less attributable to the technological maturity and wide applications of this material, although there is an urgent need to study and optimize composite sandwich structures because of their potentially wider applications. Here, to the best of our knowledge, few works have been presented to optimize the geometry of composite sandwich structures, particularly when both normal and oblique loading are considered.

This paper seeks to propose and develop a new approach for the design of composite sandwich honeycomb structures taking account both normal and oblique impact loads. The paper is organized as follows. In the first section, a FE model is established according to the low-speed impact test. In the numerical model, damage constitutive models are proposed by taking into account the intralaminar fracture and interlaminar delamination using the continuum damage mechanics (CDM) and cohesive zone methods (CZM) for composite face-sheets, and correspondingly, an elastic-plastic model for the honeycomb core. Moreover, the numerical results of the normal impact model are validated experimentally both macroscopically and microscopically. In the second section, a 45° low-speed impact FE model is built, and its responses are studied comparatively with those resulting from normal low-speed impact. Additionally, the effects of core depth and cell thickness on the low-speed impact responses of composite sandwich structures are calculated and discussed. Finally, a RSM is utilized to construct surrogate models with differences between the variables (core depth and cell thickness) and the multiple objectives (i.e. mass and the absorbed energies under normal and 45° impact), and the non-dominated sorting genetic algorithm (NSGA-II) is adopted to obtain the optimal structural parameters of the composite sandwich structure.

2. Experimental and finite element modelling

2.1. Experimental

The composite sandwich structure considered in this work was comprised of three parts: carbon fibre epoxy (CF/EP) skin panels, Nomex honeycomb (HC) core, and adhesive [8]. The skin panels were plied in a woven quasi-isotropic lay-up with a nominal thickness of 0.88 mm using Cycom 970/T300 prepregs [42]. The HC core (HexWeb HRH10-1/8-4) [43], was secondarily bonded by FM 1515-3 film adhesive [44]. The specimen dimensions were 140 mm (length) × 140 mm (width) × 9 mm (height). In terms of the HC core, the honeycomb cell is $L4.2 \times W3.2 \times H7.2$ mm (L and W denote the machine direction (roll direction), H is the cross-machine direction (web direction)). The low-speed impact test was implemented using a drop weight machine (ITR 2000). A 12.5 mm diameter spherical steel impactor was inserted at the height of 45 mm from the clamped specimen. In this drop weight test, the initial speed was stimulated and controlled by the predefined pre-pressure, which resulted in an initial speed of 3.27 m/s corresponding to the equal energy of 47.85J. After the test, the failure modes were detected using a Zeiss Ultra-plus scanning electron microscope (SEM) and an optical microscope.

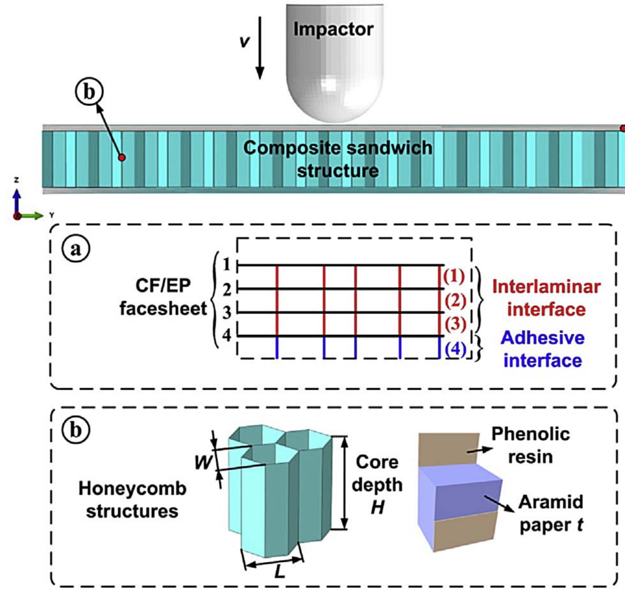


Fig. 1. Schematic diagram of composite sandwich structure subjected to low-speed impact.

2.2. Finite element model

The FE model was established and analysed by the commercial FE package Abaqus [45], and a schematic illustration of the FE model is shown in Fig. 1. First, the 12.5 mm diameter hemispherical impactor was modelled as a rigid body, and the composite sandwich structure was built as a 37.5 mm radius disk for the impact area, and the woven CF/EP face-sheet skins were modelled as 4 plies, displayed as 1–4 in Fig. 1. Additionally, the edges of composite skins were fully constrained in displacement and rotation, meanwhile the impactor was guided allowing only the z-axis displacement so as to impose an initial speed of 3.27 m/s. Furthermore, the cohesive contact based on the CZM was adopted to bond interlaminar interfaces (1)–(3) and adhesive interface (4), for predicting the damage and growth of delamination as shown in Fig. 1. Meanwhile, a general contact algorithm was applied and implemented using the penalty and "hard" contact methods. It should be noted that friction plays an important role in the analysis. In our work the friction coefficients were determined among contact surfaces. Accordingly, the friction coefficients were set as 0.3 between the surfaces of the general model [46] and 0.4 for the interaction between the cell walls of the core [47]. As the mesh method for accurate results simultaneously accounts for sufficiency, a global element size of 2 mm was defined by composite panels except for the contact centre including the specimen and impactor, where intensive elements were used to acquire satisfactory accuracy. For the honeycomb core, it was reported that a cell expansion method can reduce the calculation time by replacing the small cells with bigger ones of metal HC core [48,49]. Here,