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Crashworthiness analysis of two-layered corrugated sandwich panels under crushing loading

Chengfu Shu[a,b], Shuyun Zhao[b,c], Shujuan Hou[b,c,*]

[a] College of Mechanical and Optoelectronics Physics, Huaihua University, Huaihua, Hunan 418008, China
[b] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, China
[c] College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan 410082, China

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ABSTRACT

In this study, the energy absorption characteristic of two-layered corrugated core sandwich panels with different arrangements under quasi-static compression loading were firstly investigated experimentally. Then compared the experimental results of these two different arrangements two-layered sandwich panels, it was found that the symmetric-arranged corrugated sandwich panel has better energy absorption characteristic, which is more than 17.17% at 6 mm displacement before densification stage compare to regularly-arranged. Numerical calculations were carried out and good agreement is achieved between the experimentally results and numerical results. Finally, parameter analysis and optimization study of the symmetric-arranged two-layered corrugated sandwich panel under planar impact was carried out with crashworthiness criteria by using finite element model and response surface method. The selection of parameters in optimization study were determined by parameter analysis. The size of sandwich panel was firstly optimized for maximizing specific energy absorption (SEA). Then the multi-objective optimization of core cell shape with optimal sandwich panel size was optimized by maximizing SEA and minimizing the peak force, a Non-dominated Sorting Genetic Algorithms (NSGA-II) code was used to perform the optimization process in a gradual evolution trend, which led to obtain the Pareto front that consisted of a set of optimal objective function vectors.

1. Introduction

As a new type of composite sandwich structure, the corrugated sandwich panel has been widely used in various fields, such as high-speed trains, aerospace, housing construction and automobile manufacturing, for this structure has advantages of lightweight, noise reduction, shake-proofing, good impact resistance and good energy-absorbing capability [1,2]. Thus, the mechanical behavior, structural design and optimization of corrugated sandwich panels must be constantly in-depth investigation by researchers.

At present, numerous studies have been conducted on the quasi-static or dynamic loading properties of sandwich structures with honeycomb, corrugated and lattice truss metal cores, experimentally and numerically. Tian and Lu [3] explored bearing capacity of several different cores corrugated sandwich panels subjected to longitudinal uniform pressure with boundary condition of the simply supported on both ends. They obtained that panels with hat-stiffeners core are most efficient from a weight standpoint. Jin et al. [4] investigated the mechanical property and the failure mechanism of the integrated woven corrugated sandwich composite experimentally. It was found that 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 different orthotropic anti-shearing resistances and bending failure mechanisms. Li et al. [5] designed and manufactured carbon fiber reinforced corrugated-core sandwich cylinders (CSCs), then investigated the effects from non-wrapped and wrapped cylindrical ends by uniaxial compression tests. The results showed that with wrapped ends, the cylinders fail at end delamination and the load carrying capacity is stronger than non-wrapped ends, due to skin fracture controls the failure of the CSCs with wrapped ends. Hu et al. [6] designed and fabricated a novel carbon fiber reinforced composite lattice truss sandwich panel, than studied the strength and failure modes of the structure by compression and shearing experiments. A coupled compression-shear failure mode was observed in compression, the compression and shear strength of this structure were enhanced. Fan et al. [7] investigated the energy absorption ability of multi-layered woven textile sandwich panels experimentally, results showed that the peak load of the multi-layered structure was close to its

* Corresponding author at: College of Mechanical and Vehicle Engineering, Hunan University, Changsha, Hunan 410082, China.
E-mail address: shujuanhou@hnu.edu.cn (S. Hou).

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constituting monolayer, energy absorption of the multi-layered panel was greatly enhanced and far exceeds that of the monolayer panel of the same thickness. Liu et al. [8] studied the biological composite material sandwich structure, for which coconut mesocarp was chosen to be the core with sheets of CFRP and GFRP, and found the specific energy absorption is much higher than metal sandwich structure under three points bending tests. Chen et al. [9] predicted the damage behaviors of composite sandwich structures subjected to low-velocity perforation impact, and describe the key perforation mechanisms and associated damage patterns. Qin et al. [10–12] studied the low-velocity impact response of sandwich structures with metal foam core theoretically. They obtained the analytical expressions when considering the interaction between the plastic bending and stretching, and considering the effects of local denting and foam core strength on the overall deformation of the sandwich beams. Kılıçaslan et al. [13] explored the deformation process, quasi-static and dynamic responds of multi-layer corrugated sandwich panels under local impact with different speeds experimentally and numerically, which demonstrated that the increase of critical buckling stress at high strain rate was attributed to micro-inertial effects. Hou et al. [14] investigated the multi-layered corrugated sandwich panels experimentally, and found that the sandwich configuration and number of layers played important role in the failure mechanism and energy absorption. Zhang et al. [15] investigated the dynamic response of fully clamped multilayer sandwich beams with slender metal foam core, and elucidated that the dynamic and quasi-static solutions can capture the low-velocity heavy-mass impact response of fully clamped slender multilayer sandwich beams.

In our previous work [16,17], we investigated the effect of key shape and dimensional parameters on the crashing behaviors of honeycomb and corrugated sandwich panels and optimized the sandwich core configurations for crashworthiness criteria. As a continuation of our previous work, in the current study, we researched the two-layered corrugated sandwich panels subjected to out-of-plane compression loading experimentally, and conducted the parameter analysis and optimization of the two-layered symmetric-arranged corrugated sandwich panels under planar impact by using the finite element techniques and response surface method. This type of two-layered corrugated sandwich structure can constitute different arrangement flexibly, and as the simplest structure of multilayer sandwich structure, it can provide a research foundation and some useful guidance for the design of multilayer corrugated structures.

2. Materials and methods

2.1. Panel construction

The basic form of two-layered corrugated sandwich panel is described in Fig. 1a, in which H_{f_1}, H_{f_2}, H_c, t_2, a and b denotes the upper face sheet thickness, lower face sheet thickness, monolayer core height, interlayer sheet thickness, total length and width, respectively. The trapezoidal corrugated core cell shape is depicted in Fig. 1b.

Trapezoidal corrugated core was manufactured by using self-made molds which were installed at the hydraulic punch equipment shown in Fig. 2a. The liner cutting method was adopted to obtain plates for getting accurate specimen size, and put the plates in the middle of the two self-made molds. Exerted pressure through the hydraulic equipment and kept a certain amount of time repeatedly in order to obtain the corrugated trapezoidal core as shown in Fig. 2b. The parameters of the manufactured core specimens are listed in Table 1.

Two different arrangement of the corrugated sandwich panels with two-layered core, namely regularly-arranged and symmetric-arranged, were constructed by stacking the trapezoidal corrugated aluminum core and aluminum sheets between the face sheets. The core and interlayer sheets were made of 5052-O aluminum alloy plates with a thickness of 0.2 mm and the face sheets were made of 2024 aluminum alloy plates with a thickness of 1 mm. An epoxy adhesive was used to bond the face sheets and the cores and interlayer sheet for not less than 24 h under constant pressure at ambient temperature. The prepared regularly-arranged and symmetric-arranged corrugated sandwich panels with two-layered core are displayed in Fig. 3, respectively.

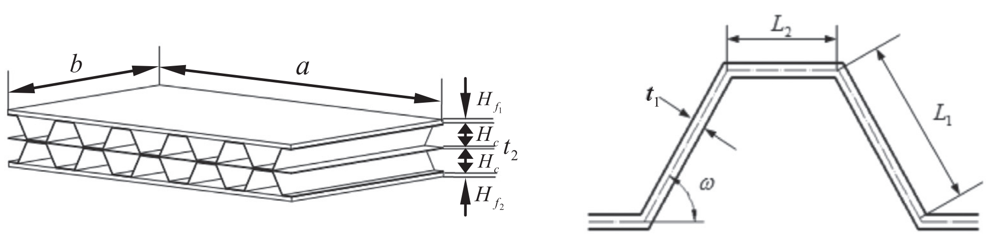
2.2. Experiment and discussion

The quasi-static compression tests of the two-layered corrugated sandwich panels were carried out at low speed of 2 mm/min through an upper smooth indenter in the INSTRON-5984 test machine in accordance with ASTM: C365/C365M, which provides a standard method of obtaining the flatwise compressive strength. Two different arrangement specimens were tested with an identical dimension, for which the overall structure size was $a \times b = 70\ \text{mm} \times 70\ \text{mm}$. The specimen was placed on the lower platform as shown in Fig. 4. The data of the force and displacement in the loading process were transferred from the sensor mounted in the test machine to the computer.

Fig. 5 shows the comparison of experimental results for these two types of two-layered corrugated sandwich panels, including force-displacement curves and energy-displacement curves that can be obtained by integrate the force-displacement curves. From Fig. 5a, it is can be seen that the force of symmetric-arranged corrugated sandwich panel is larger than regularly-arranged corrugated sandwich panel in the elastic stage, and the platform force is near 1 kN for both corrugated panels. Regularly-arranged corrugated sandwich panel enter the stage of densification earlier with the critical displacement of 6 mm than symmetric-arranged corrugated sandwich panel with the critical displacement of 7.5 mm. From Fig. 5b, one can see that the energy absorption of symmetric-arranged corrugated sandwich panel is larger than regularly-arranged corrugated sandwich panel before densification stage, more than 17.17% at 6 mm displacement. Therefore, one can draw the conclusion that the compression performance of symmetric-arranged corrugated sandwich panel is better than regularly-arranged corrugated sandwich panel.

2.3. Numerical simulation and validation

The two-layered corrugated sandwich panels were also analyzed by using the explicit FE code ANSYS/LS-DYNA. The face sheets, corrugated core and interlayer sheet were meshed using quad Belytschko-Tsay shell



(a) two-layered corrugated sandwich panel (b) core cell shape

Fig. 1. The configuration of two-layered corrugated sandwich panel and core cell shape.