International Journal of Impact Engineering 113 (2018) 98–105

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

On the influence of the property gradient on the impact behavior of graded multilayer sandwich with corrugated cores

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ARTICLE INFO

Keywords:
Graded multilayer sandwich
Corrugated core
Impact testing
Energy absorption efficiency
Property gradient

ABSTRACT

Graded lightweight structure is a new trend to improve energy absorption capacity of such structural materials. This study aims at the influence of property gradients on the overall behavior of graded multilayer sandwiches with corrugated cores under impact loading. The design of the property gradient of graded multilayer sandwiches as well as the manufacturing of different corrugated cores is presented at first. The graded multilayer sandwich is tested under various experimental configurations at rather low (9 m/s) and high (38 m/s) impact velocities. It turned out that no influence of gradient is found for low impact velocity because a quasi-static equilibrium state is reached. However, at high impact velocity, the test revealed a significant difference between different property gradient profiles. Numerical models are also built to simulate those tests. It allows for the further numerical analysis on a larger range of gradient profiles and higher impact velocities. A general trend for the design of the graded multilayer sandwiches with corrugated cores to improve energy absorption efficiency is proposed, which consists of placing the weakest layer near the protected structure and the hardest layer near the impacted end of the graded sandwich.

1. Introduction

Lightweight structures (honeycomb, foam and corrugated plate, etc.) combining both lightweight and energy absorbing capacities are widely used in industrial applications such as automobiles, naval vehicles and aircrafts [1]. They attract many academic interests and a great number of investigations are reported in the past decades [2–7].

A new trend is to introduce a property gradient in the cellular core to improve the energy absorption capacity at a constant weight [8–10]. Indeed, a variation in the cell number distribution or material strength may significantly influence their energy absorption properties. Such graded material can also be easily found in the nature. For example, the dermal armor of ancient palaeoniscoids possess a kind of multilayer structure consisting of four different organic–inorganic nanocomposite material layers [11]. Therefore, significant progress has been made in the past decade to explore the compressive responses of graded sandwiches under dynamic loading. Gupta [9] studied the hollow sphere (microballoon) filled syntactic foams with a graded density profiles. Zeng et al. [8] studied graded hollow sphere agglomerates possessing a density gradient by varying the inner diameter the sphere. Their results showed that placing the hardest layer as the first impacted layer and the weakest layer as the last layer had some benefits in terms of maximum energy absorption with a minimum force transmitted to the protected structures. Ajdari et al. [12] and Shen et al. [13] studied numerically the dynamic crushing of functionally graded material. Three deformation modes had been proposed when the strongest layer was placed at the impacted end while two deformation modes were observed when the weaker layer was placed at the impacted side. Results showed density gradients could significantly change the deformation mode and the energy absorption. Theoretical analysis on the basis of propagation of shock front in a graded media has also attracted some interests [14–17].

The current study is aimed at the understanding of the role played by the gradient profile in the dynamic behavior of graded multilayer sandwich with corrugated cores. Graded multilayer sandwich specimens are designed by changing the numbers of inclined struts. Experimental study at different impact velocities will be performed using a large diameter Hopkinson bar facility. Numerical model will be also introduced to reproduce the experimental observations and will be used to simulate virtual testing results at higher impact velocities. Finally, a strategy for a better energy absorption efficiency will be proposed.

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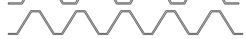
https://doi.org/10.1016/j.ijimpeng.2017.11.017
Received 15 June 2017; Accepted 25 November 2017
Available online 01 December 2017

Table 1
Schematic diagram of corrugated sheets with various numbers of cells.

Cell number	Inter-distance (mm)	Schematic diagram
3	7.6	
4	4.9	
5	3.2	
6	2	

2. Graded multilayer sandwich with corrugated cores

2.1. Gradient design

Multilayer sandwiches with corrugated cores are composed of several layers including the interlayer skin plate and the corrugated cores. The property gradient across the layers is obtained by changing the density of the corrugated core of each layer. The parameters controlling the density of the corrugated core are the base material, the plate thickness, the inclined angles and number of corrugated struts. In order to have rather homogeneous behaviors of the layers, it is chosen to only change the number of struts in this study.

For example, it is possible to make a progressive gradient profile using four layers containing 3 to 6 pair of struts. Table 1 lists the inter-distance between the pair of struts and schematic diagrams of corresponding corrugated cores.

If we denote this up size gradient profile as C3456 for layers containing 3, 4, 5 and 6 pairs of struts from front to back face, we can also make a down size gradient profile C6543. It is noted that C6543 means strongest layered is at the impacted end (no matter the different testing configurations) Two other profiles of harder external/inner layers C6336/C3663 are also interesting because of the same mass with C3456/C6543.

2.2. Corrugated cores manufacturing

0.5 mm aluminum 1060-O sheets are used to form the corrugated core. Such a choice of the base material is interesting for impact testing because of its quasi rate insensitivity. Indeed, quasi-static tests and impact tests are performed with a dog-bone type specimen. The size and a photo of the specimen are plotted in Fig. 1. Fig. 2 shows a comparison of their stress–strain curves under quasi-static loading (0.001/s with uniaxial testing machine) and dynamic loading (300/s with split Hopkinson tension bar). No significant difference is observed for the two stress–strain curves. It is noted that the aluminum 1060-O sheet is not brittle at all. The limited strain of 6% in Fig. 2 is only due to split Hopkinson tension bar (SHTB) impulse length limitation.

The forming process of corrugated core is schematically illustrated in Fig. 3. The aluminum rectangle plate is put along the lower mould meeting the limit line and clamped with the lower mould and the upper mould (Fig. 3a). The whole punch-die system is put into a universal testing machine and compressed down for 9.5 mm at 0.1 mm/s, generating the first cell (Fig. 3b). The maximum compressive load is limited to 1500 N to prevent undesired over compression of the sheet. Such a process can be repeated by moving the sheet rightwards to shape next cells (Fig. 3c). The technical details can be found in [18].

The rectangle graded sandwiches with corrugated cores are manufactured using the technique developed in our previous work [18]. Four types of moulds are made to produce four corrugated cores with

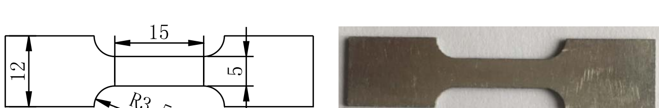


Fig. 1. Dog-bone specimen of base material Al 1060-O.

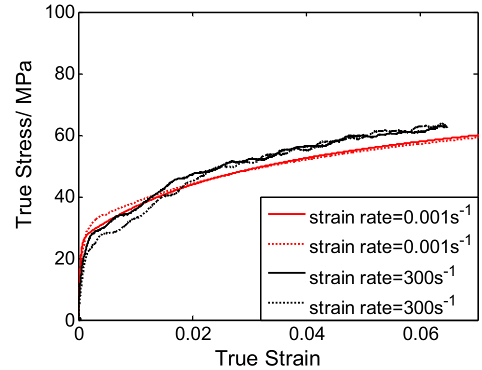


Fig. 2. Stress–strain curves of AL 1060-O.

different inter-distance of the strut pair (Fig. 4).

2.3. Graded multilayer specimen

In order to put multilayer specimen inside the pressure bars of 97 mm diameter, the specimen's size is limited. The whole length of six cells is 80.5 mm, so the depth of corrugated core is chosen to be 50 mm. For a single layer, the specimen is assembled by bonding the corrugated core with the 80.5 × 50 mm aluminum skin plates of thickness 1 mm, in which adhesive (3 M DP810) is spread out over the rectangle skin plates and then the two adhesive planes as well as the corrugated core are put together under a weight until the complete solidification of the adhesive. The whole graded specimen can be manufactured by repeating the aforementioned bonding process. The scheme and the photograph of assembled graded sandwich (C3456) are shown in Fig. 5.

3. Behavior of graded corrugated cores sandwich under impact loading

3.1. Direct impact test using a large diameter Hopkinson pressure bar

Hopkinson pressure bar is a largely used technique in impact testing [19,20]. It provides an accurate measurement of forces and velocities at the specimen/ pressure bar interface [21,22]. It is then preferred here to other known common testing device (shock tube, high speed testing machine or drop weight facilities).

Because of the size of specimen (80.5 mm × 50 mm), a large diameter bar is needed to host the specimen. Besides, as the sandwich is rather weak in strength, a low strength Nylon bar should be used for the impedance match. Another difficulty is the length of loading pulse. Indeed, assuming that we need to compress the four-layer sandwich till compaction around a displacement of 40 mm. The time needed at an impact velocity of 10 m/s is 4 ms. In a conventional SHPB version the input bar's length should be 8 m and a projectile of 4 m for a Nylon bar system at least, which is hard to be achieved in a laboratory.

For these reasons mentioned above, a direct impact Hopkinson bar configuration is chosen. A large diameter (97 mm) Nylon direct impact Hopkinson bar set-up is proposed and its schematic drawing is depicted in Fig. 6.

The specimen is put at the front of the pressure bars (2 × 4 m), and the projectile of 800 mm long can directly impact the specimen. The projectile is made of the same material as the pressure bars (Nylon PA66) and it is launched to the desired striking velocity by a gas gun as that used in a common Hopkinson bar system. Two 4 m bars together will serve as a 8 m output Hopkinson bar and there is no loading pulse limitation with direct impact configuration. Longitudinal strains are measured by means of three pairs of diametrically opposite strain gages located at three positions 1, 2 and 3, which are useful for the dispersion correction [22–24]. It leads to the determination of the force and the velocity at the interface between the specimen and the pressure bar by