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Behaviour of fibre-reinforced honeycomb core under low velocity impact loading

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ABSTRACT

In this study, the behaviour of two different types of cores, short flax fibre reinforced and continuous flax fibre reinforced polymeric cores, is investigated under low velocity out-of-plane impact loading. The fibre-reinforced corrugations were manufactured by using matched-die compression moulding and the resulting cells were bonded using ultrasonic methods to form recyclable honeycomb cores. A drop weight impact tester, Imatek IM10T-20 ITS, capable of producing velocities up to 20 m/s coupled with a high-speed camera (*Phantom*), was used to capture video images of the impact. The displacement of the impactor was recorded with a digital displacement transducer and the force was recorded with a digital force transducer. The effects of reinforced material type, the core height and the presence of face sheets including all their interactions on the energy absorption are determined by using statistical analysis based on the Taguchi method. The impact results reveal a better energy absorption when honeycombs with cell walls reinforced with continuous fibres are used; the presence of face-sheets plays an important role in energy absorption only at lower core height. This is confirmed by the results of the statistical analysis revealing antagonistic interaction between the core height and face sheets.

1. Introduction

Structural crashworthiness is a critical consideration in many engineering applications. The design of structures that are capable of withstanding and mitigating the effect of impact requires both knowledge of structural dynamics and understanding of the properties and deformation mechanisms of the materials and components used. Honeycomb cores have been used as efficient energy attenuators due to their hollow tube-like structure and their cellular arrangement. The *Apollo 11* is a classic example, where crushable metal honeycombs have been used in all the four legs of the landing module to absorb impact energy during landing [1]. For effective energy absorption during impact loading it is desirable to have a system that exhibits large plastic deformation behaviour, with the effect to absorb all the impact kinetic energy. However, in order to achieve this, it is important to set tolerable limits on the magnitude of the force transmitted, which is often achieved through rigorous experimentation. Earliest work on the crushing behaviour of honeycomb cores was developed in 1960s by McFarland [2], which was then modified by Wierzbicki [3] who identified the collapse of the cell walls to be due to the folding of the element which is accomplished by the rolling type of mechanism and not due to shear type of deformation as described by McFarland. Zhang and Ashby [4] extended this approach to develop expressions for the failure loads of honeycombs under transverse compression and shear loading, which agree well with the experimental data for aramid paper honeycombs. Wu and Jiang [5] focussed on the investigation of the crushing phenomena of honeycomb structures under both quasi-static and dynamic loading conditions considering the effects of cell dimension, material strength and number of cells under loading. They found that the energy absorption is dependent on the cell size and the core height and they recommend honeycombs with smaller cell size and core heights for higher energy absorption under quasi-static and impact loading conditions. The effect of low velocity impact on aluminium honeycombs was investigated by Hazizan and Cantwell [6] in 2003, with a simply energy balance method being used to classify the energy absorption of a honeycomb sandwich structure into bending, contact and shear components. It was also concluded that the materials used for their testing were not rate-dependent and as such could also be used for modelling of dynamic behaviour. Further, Yamashita and Gotoh [7] investigated the effect of the cell shape and the cell wall thickness on crush behaviour under quasi-static conditions numerically. Their results showed cell wall buckling to be a predominant mode of failure during cyclic loading and the crush strength increased with decrease in cell wall angles and increase in cell wall thickness.

Taken together, the energy absorption in a honeycomb core is dependent on the compressive behaviour of the core under different loading conditions, which in turn is dependent on the geometric

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parameters of the core [8]. Three common modes of failure occurring during compression loading are fracture of the material, buckling of the cell walls and de-bonding at the double thickness cell walls interface. A generalised stress–strain curve depicting the regions of energy absorption is shown in Fig. 1.

In the linear-elastic region, most of the material deformation is recoverable. As the compressive load progresses, the cell walls shorten in the direction of the loading and elastic buckling occurs, during which the cell walls begin to bend and bulge. This buckling in the core is governed by the bending of the cell walls in essence proportional to the cell wall thickness-to-length ratio or to the relative density of the core [10]. After elastic buckling, if the cell wall material is brittle, it will typically fracture after this region and in the case where the material yields, the cell walls start to develop hinge lines and the material will begin to collapse along those lines in a similar fashion to that of a piano accordion. This region is referred to as the plateau region, and the cell wall material is plastically deformed. As the cell wall material proceeds to collapse it reaches a densification region after which no energy absorption can be expected (depicted as a vertical line in Fig. 1). For many packaging applications, it is desirable to have a long uniform plateau region [11] in order to absorb the impact energy before the packed material hits the ground. For honeycomb cores to enter into the plateau region and exhibit plastic deformation behaviour, the cell wall material must yield and not fracture immediately after the linear-elastic region, in effect consuming the impact energy to plastically deform the cell walls. Conventional honeycomb cores such as aluminium and Nomex™ offer energy absorption but this could be enhanced by the use of viscoelastic thermoplastic materials. Cores that are made from thermoplastics not only improve the energy absorption but also offer advantages such as reduced density and recyclability. Thanks to the aforementioned properties this new class of honeycomb core could potentially replace conventional cores, in non-structural components such as cabin/wall dividers, foot rests, seat backing, door trims and galleys, where functional requirements are more stringent than the others.

However, the strength and stiffness of such cores are limited due to the inherent properties of the thermoplastic materials. Therefore, in view of improving the strength and stiffness of the thermoplastic materials without sacrificing other properties, natural fibres can be used as reinforcements in the cell walls of the cores [8]. The effect of reinforcement types discontinuous and continuous reinforcement and impact type (bare and stabilised) on the energy absorption are investigated in this study. Because there are several parameters involved, determining the effect of each parameter on the energy absorption individually and also obtaining their synergistic effect on the same is difficult and time consuming. Therefore, a L_8 full factorial Design of Experiments (DoEs) is used to study the effects of the parameters and their interaction on the overall absorption in the core.

2. Materials and manufacturing

The materials used were as follows:

- Linear Low Density PolyEthylene (LLDPE) films with a density of 0.91 g/cm^3 were used as matrix.
- Unidirectional flax fibre mat (UD180 – C003) of 180 g/m^2 from Lineo, Belgium and random fibre mat of ~200 g/m^2 from Sachsen-Leinen GmbH, Germany were used as reinforcement.
- Glass fibre-PP tape, Plytron™ with a thickness of 1 mm was used as the face sheet material.

The cores were manufactured by using a film-stacking process where the dry flax mat and LLDPE films were interleaved and laid between half hexagonal matched-dies with heating and cooling ability. The matched-die was heated to ~170 °C after closing the mould at 500 mm/s, a constant forming pressure of ~0.5 MPa was maintained during the heating cycle for consolidation and the formed part was cooled within the die to avoid spring-back. The half-hexagonal corrugations were laser cut to 20 mm and 40 mm, which were then assembled and bonded using ultrasonic methods, Fig. 2.

3. Mechanical testing

All specimens were tested in an Imatek (model IM 10T-20ITS) drop weight impact tester equipped with a high-speed camera, *Phantom*, capable of capturing 250,000 fps.

The displacement and the impact force were recorded using digital transducers. A 165 mm diameter flat striker with a mass of 16.46 kg was used as an impactor to test the samples, five for each configuration, that were placed on a flat platen anvil. The maximum allowable energy, set to 90 J, was determined after several trials such that all the specimens considered in this study were subjected to consistent impact energy.

For the core material, tensile tests were conducted using the ASTM standard test method D3039 [12], compressive and in plane shear tests were performed as per ASTM D6641 and ASTM D4255 specifications respectively [13,14] using an Instron universal testing machine (Model 5567).

4. Design of experiments

Energy absorption in honeycomb cores is usually higher in the out-of-plane direction because of their higher load carrying capacities in that direction. As the absorption depends on the material properties, two different reinforcements, unidirectional continuous and short random fibres, were used as reinforcement in the cell walls with unidirectional continuous flax fibres orientated in the out of plane direction of the core. Additionally because the

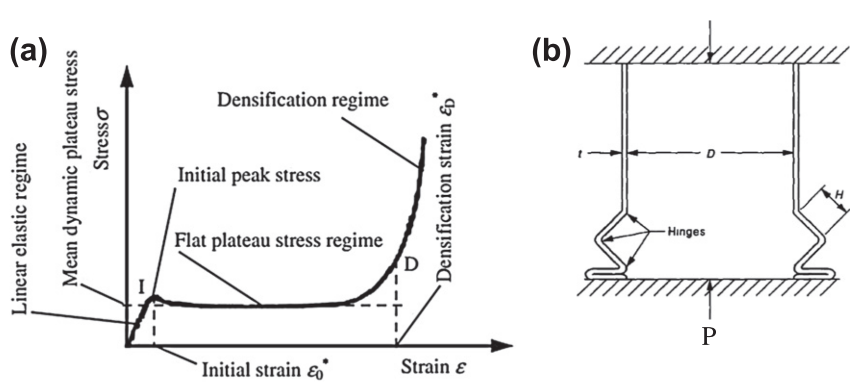

Fig. 1. (a) Generalised stress–strain curve used for calculating energy absorption and (b) buckling and fracture failure mechanism [9].