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The blast resistance of stitched sandwich panels

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ABSTRACT

The effect of through-the-thickness stitching on the blast resistance of sandwich panels is investigated both experimentally and numerically. Panels based on three-dimensional woven S-glass/epoxy skins and a crosslinked PVC core were manufactured using a vacuum assisted resin infusion process. The panels were stitch-bonded using Kevlar 129 yarn, by means of a multi-needle stitch-bonding machine developed in a previous investigation. The performance of both orthogonal (0°) and biased (45°) stitching procedures were considered and their respective responses were compared to that of a similar unstitched panel. The blast resistance of the sandwich panels was modelled using finite element techniques.

An examination of the blast-loaded samples highlighted a number of failure mechanisms, including crushing of the foam core, skin-core debonding, fracture of the glass fibre/epoxy skins, fibre-matrix debonding with fibre pull-out and delamination. If evaluated on the basis of specific impulse (applied impulse normalized by plate mass), the results indicate that stitching has no obvious effect on the blast resistance of the sandwich structures. Agreement between the finite element models and the experimental data was good over the range of loading conditions considered. Here, the FE models accurately predicted the overall deformation responses of the panels and also captured the primary failure modes.

1. Introduction

Due to their low weight and excellent flexural properties, sandwich structures consisting of strong and stiff composite skins bonded to a low density core are currently being used in significant quantities in a wide range of engineering structures. To take advantages of their attractive dynamic properties and overall light weight, engineers have been considering such structures for use in blast-loaded components [1–10]. The dynamic response of a sandwich structure is dependent upon many parameters, including the properties of the skins, the compressive/shear moduli of the core, the strength of the core, as well as the strength of the bond between the skin and core. In many cases, the strength of the sandwich structure is controlled by the failure characteristics of the core material and the skin-core interface.

There are currently a number of different approaches for enhancing the delamination resistance, impact damage tolerance and joint strength of sandwich structures based on composite skins. Z-pinning is one such method and a number of studies have been undertaken to investigate the compression properties of z-pinned composites [11–15], their delamination resistance [16–22] as well as the behaviour of z-pinned joints [23–28]. Mahfuz et al. [29] investigated the low velocity impact response of sandwich structures with a titanium z-pin reinforced foam core. For the energy levels considered, they found that by reinforcing the foam cells with z-pins, low velocity impact damage can be effectively contained. Zhang et al. [30] studied the low velocity impact resistance of z-pinned carbon/epoxy composites and found that z-pinning reduced the impact damage area by between 19 and 64%, depending on the impact energy level and laminate thickness. Childress and Freitas [31] observed reductions of 30–50% in the amount of damage sustained by hailstone impacts when employing z-direction pinning. They found that damage is reduced by bridging traction forces that are generated by the z-pins. This in turn serves to increase the delamination toughness. Research on z-pinned sandwich structures subjected to shock loading is relatively limited. Z-direction pins have been used to modify the core and improve

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overall response of sandwich panels to high strain-rate impact loading [32]. Rice et al. [33] investigated the failure modes in carbon fibre sandwich beams reinforced with Z-pins when subjected to three-point bending.

One of the most effective ways to enhance the impact and blast resistance of foam-based sandwich structures is to stiffen and strengthen the core and increase the level of interaction between the skins via through-thickness stitching. Raju and Tomblin [34] investigated the energy absorbing characteristics of sandwich panels with through-thickness stitches, subjected to edgewise compression. Static crush tests showed that the average sustained crush load increases with reduced stitch spacing, thereby increasing the total energy absorbed. Researchers [35–37] have also investigated the response of stitched panels under flexural, shear and compressive loads. They found that the mechanical properties increase significantly following the introduction of stitches with stitch density being a significant factor. The fatigue behaviour of stitched foam-core sandwich structures has also been investigated [38,39]. Kim et al. [38] studied three types of specimens (non-stitched, stitched and stiffened sandwich specimens) with glass fabric faces and a polyurethane foam core. The bending strength of the stitched specimen was improved by 50% compared with the non-stitched specimen, and the stiffened specimen was over ten times stronger than the non-stitched specimen. It was found that fatigue characteristics are not greatly affected by the variation of stitching thread diameter. In addition, the effect of stitch density and stitch thread thickness on damage progression and the failure characteristics of stitched composites under out-of-plane loading has been studied [40]. Nondestructive inspection techniques including ultrasonic C-scan, X-ray radiography and X-ray micro-computed tomography were used to elucidate and clarify the damage mechanisms. It was shown that the final failure load increases with increasing stitch fibre volume fraction.

The impact resistance of foam-based sandwich structures can also be enhanced by the introduction of through-thickness stitching [41–44]. Lascoup et al. [42] evaluated the damage resistance of sandwich structures based on a stitched foam core and glass fibre face-sheets under low velocity impact loading. They found that the impact resistance of the sandwich structure was greatly enhanced by the introduction of stitches and showed that the global behaviour under impact loading is influenced by the geometrical stitch parameters. Few workers have investigated the blast resistance of stitched foam core sandwich structures. Tekalur et al. [44] investigated the shock loading response of sandwich panels based on 3-D woven–E-glass composite skins and a stitched foam core. Both experimental work and theoretical analyses were carried out to evaluate the effect of core stitching density on the transient response of three simply supported sandwich panels loaded in a shock tube. The experimental results highlighted the transient deformation, the mechanisms of damage initiation and progression as well as final failure in sandwich composites with unstitched and stitched foam cores.

Finite element analysis techniques have been employed to simulate the mechanical performance of stitched foam core sandwich structures. Shigan et al. [45] developed finite element models to study the effect of stitching angle on the mechanical properties of stitched sandwich panels. The flexural response of stitched foam core sandwich structures with carbon/epoxy skins were also simulated by the numerical modelling [46]. Based on Eshelby's tensor and the Mori–Tanaka equivalent model, a new model was proposed to predict the flexural rigidity of stitched foam core sandwich structures.

In this paper, the effect of through-the-thickness stitching on the blast resistance of sandwich panels is investigated both experimentally and numerically. Panels based on three-dimensional woven S-glass/epoxy skins and a crosslinked PVC core are subjected to blast loading using plastic explosives and a ballistic pendulum.

2. Experimental procedure

2.1. Manufacturing of the sandwich samples

The core materials in the sandwich preforms tested in this investigation were based on a crosslinked PVC foam (Divinycell H from the Diab Group) with a density of 130 kg/m^3 and a thickness of 12 mm. The skins consisted of a three-dimensional (orthogonal) woven S-glass fabric with an areal density of 800 g/m^2. Two of the three panel configurations contained stitches linking the outer composite skins through the foam core. The panels were stitch-bonded using a Kevlar 129 yarn, by means of the multi-needle stitch-bonding machine developed by Aktas et al. [47]. The stitch-bonding method was based on a modified lock stitch, in which the stitching yarns were inserted from one surface of the sandwich preform and then locked on the other surface via a locking yarn. The stitch density was 1 cm × 1 cm. Further details of the stitching procedure can be found elsewhere [48]. Panels with orthogonal (0°) and biased (45°) stitches and well as a control panel without stitches, were prepared and impregnated using a vacuum assisted resin infusion process involving a cold-curing epoxy resin system (Araldite LY 5052-1 resin and Aradur 5052-1 hardener). The curing conditions of the sandwich samples followed those recommended by the resin manufacturer and involved a gelation stage of 16 h at 25 °C and a post-curing stage of seven days at 25 °C.

2.2. Blast testing

In preparation for blast testing, four 12.7 mm diameter holes were drilled into the corners of the 150 mm square sandwich panels, Fig. 1(a). The panels were then clamped between two steel plates, to give a circular exposed area with a diameter of 90 mm. The panels were subjected to blast loading by detonating discs of PE4 explosive placed at a distance of 90 mm from the front surface of the panel. The detonator was attached to the explosive using an additional small quantity of the PE4 explosive. The explosive charge was positioned at the open end of a circular steel tube attached to the front clamping frame. When the explosive was detonated, the blast load was directed down the tube thereby loading the specimen. The test fixture, including the two clamping frames and the transmission tube, were attached to the ballistic pendulum shown in Fig. 1(b). Table 1 details the panel masses and impulses used during the blast tests on the sandwich panels.

2.3. Numerical procedure

Finite element models were developed using the commercial code Abaqus/Explicit [49] to simulate the blast response of PVC foam sandwich panels with GFRP skins and Kevlar stitches. Here the PVC foam was modelled as a crushable foam [50] subjected to compressive loading with rate-dependent strain hardening and both shear and ductile failure criteria. The phenomenological yield surface for the foam is given by:

$$\Phi \equiv \frac{1}{\left[1+(\alpha/3)^2\right]}\left[q^2+\alpha^2\sigma_m^2\right]-\sigma_y^2 \le 0 \qquad (1)$$

where q is the Von Mises stress, σ_m is the mean stress, σ_y is the yield strength of the foam in uniaxial tension or compression. In Eq. (1), α defines the shape of the yield surface [49], which is related to the