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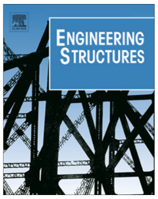

Numerical analysis on the effect of shear keys pitch on the shear performance of foamed sandwich panels

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ABSTRACT

The main problem associated with using composite sandwich panels with foam core is their ability to withstand shear load. The aim of the present work is to extend the knowledge of mechanical properties both on constituent components and on the whole sandwich structures, focusing on the effects induced by inserting semi-circular shear keys between the skin and the foam core. The sandwich panel under investigation is composed of glass fibre reinforced polymer (GFRP) skin with polyvinylchloride (PVC) and polyurethane (PU) foam core, while the shear keys are made of chopped strand (CS) glass fibre impregnated with epoxy resin. The material properties of the skin, keys and foam core materials were investigated through a series of quasi-static tests. The mechanical properties of each component were used as input data in order to implement the finite element (FE) analysis using ABAQUS software. Parametric investigation using the FE analysis to select the most suitable pitch (space between shear keys along the panel) of the shear keys taking into consideration the materials and geometrical nonlinearities as well as the complex interaction between all the mating surfaces was performed. Five different pitches have been investigated namely 15, 25, 35, 45 and 55 mm. The results showed that the model with 45 mm pitch represents the most sustainable model among the others. The FE results were verified with the measured ones extracted from the out-of-plane shear test.

1. Introduction

Composite sandwich structures fabricated by attaching two thin but stiff skins to the lightweight but thick core have been widely used in the automotive, aerospace, marine and other industrial applications. This material has also been identified as a very interesting alternative to traditional materials because of its high bending stiffness and high strength to weight ratios. Composite sandwich structures possess many features that make them applicable in many purposes, among these features are: high relative flexural strength and stiffness [1,2], high impact strength [3–6], high corrosion resistance [7,8] and the low thermal and acoustics conductivity [9–11]. However, the design of composite sandwich structures is a critical issue because it needs a reliable test results of the mechanical response of the skin and the core materials including materials nonlinearity and proper failure criteria under complex loading state [12–15].

In spite of the many advantages of the composite sandwich panels, it was found to be notoriously sensitive to failure by shear load with a premature failure of skin–core debonding. However, limited attempts have been done to characterize and enhance the interaction between the skin and the core materials. This might be attributed to the complexity of the interaction or the ability of the finite element (FE) software to evaluate it.

One of the earliest attempts to improve the connection between the sandwich components was stitching [16,17] which included sewing of the laminates through the thickness using high strength yarn. Although this technique acquired a lot of attention due to its ability to enhance the through thickness properties of the laminate, it failed to find many applications because of the deterioration of the in-plane properties of the structure before it was placed in application [18]. Mouritz et al. [19] and Mouritz and Cox [20] reported a significant reduction in the in-plane mechanical properties of the composites enhanced with stitching, these degradations including Young's modulus, strength and fatigue resistance.

Z-pinning technique was another method to improve the sandwich action of the laminate by inserting metallic or fibrous pins through the thickness of the composite using ultrasonic gun [21–23]. It was observed experimentally and validated numerically that incorporating of z-pins in the laminate would result in a remarkable deterioration in the in-plane elastic properties including Young's modulus, shear modulus as well as tensile [23], compressive [24–26] and bending [27] strengths. In addition, it was

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observed that as the volume content of the z-pins increased (which was necessary for proper connection within the laminate), as the deterioration in the in-plane properties increased. Chang et al. [23,27] attributed the deterioration in the fatigue life under cyclic tensile and flexural loading to the development of fatigue-induced damage at the clusters of broken fibres near the z-pins. While the reduction in the compressive fatigue performance was due to progressive rotation of the wavy fibres near the z-pins with increasing the number of load cycles, which accelerated failure by micro buckling and kinking [25]. In addition, the swelling phenomenon, resulted from performance of the laminate.

For marine applications, peel-stopper technique was profusely implemented to reduce the risk of the delamination of the outer skin from the ship hull by introducing a connection between the outer and inner skins. The primary versions of this technique had many drawbacks due to the lack of the structural integrity of the sandwich panel as a result of the mandatory connections between the outer and inner skins [28]. The later versions [28–30] of this technique were simple and based on another structural rule. The main principle of these versions was that the skin with a peel-stopper should have approximately the same in-plane strength as the skin without a peel-stopper, but a much lower bending strength. Thus, if the separation started and propagated towards the peel-stopper, then the skin would break off due to bending by the peel-stopper and the peeling would thus be arrested. It was investigated experimentally and numerically the influence of the peel-stopper on the mechanical behaviour and the skin–core interaction of the foamed sandwich panels [31]. It was concluded that introducing the peel-stopper would hinder or eliminate the skin–core delamination but due to the manufacturing difficulties and high expenses, its utilization in many applications was restricted.

Consequently, there was an obvious need to develop an easy and economical solution for improving the shear performance and the skin–core delamination resistance of the foamed sandwich panels. A novel concept of shear keys by milling out semi-circular grooves in the foam sheet and fill them with a pre-preg glass fibre before bonding the face sheets was proposed by Mitra [32]. The experiments showed the significant effect of the shear keys on the shear response and the link between the skin and the core under out-of-plane shear load. In addition, for the specimens with initial delamination under compressive load, 25% improvement in debonding resistance was noticed in the specimens with shear keys compared to the specimens without shear keys [33].

The effect of shear keys pitch (space between shear keys along the panel) on the shear performance of the composite sandwich panel with foam core needs to be investigated deeply to stand on the most appropriate pitch value that offers the highest shear strength. This will make the implementation of the shear keys methodology in many applications more feasible. This paper investigated numerically the effect of the pitch variation of the chopped strand (CS) shear keys on the shear performance of the glass fibre reinforced polymer (GFRP)/epoxy sandwich panels with polyvinylchloride (PVC) and polyurethane (PU) foam core. Five shear key pitch values 15, 25, 35, 45 and 55 mm at fixed diameter of 8 mm were investigated. 3D FE model using ABAQUS software for the keyed sandwich panel was generated with different pitches to evaluate the effect of pitch variation on the shear response and the expected damage modes. The experimental study, included a comprehensive material testing program of the constituent components and the out-of-plane shear test of the entire sandwich panels, was performed to assess the shear response of the panel and validate the numerical results. Furthermore, a comparison between the experimental and the numerical shear performance of the ordinary and keyed sandwich panel was also presented.

2. Materials testing

The core materials chosen for the composite sandwich panel in this study were a closed cell PVC foam with a density of 100 kg/m^3 (manufactured by DIAB Inc. and marketed under the trade name of Divinycell H100) and a commercial closed cell semi-rigid PU with a density of 62 kg/m^3. The thickness of the foam core sheets supplied by the manufacturer and used in the current investigation was 30 mm. The foam was sandwiched between two 2 mm thickness GFRP face sheets (skin), each of which was composed of eight layers $(0, 90, +45, -45)_s$ of 2×2 twill weave E-glass GF285T2/1270 supplied by Lavander-CE Pty Ltd. Two parts epoxy adhesive, designated as West Systems 105B Epoxy resin and West Systems 206C slow hardener, used in a 5:1 proportion of resin to hardener was utilized for the resin infusion. The CS glass fibre was mixed to the same epoxy resin used in the construction of GFRP skin, while the chopped fibre content was kept to 15% wt.

Standard material characterization tests were carried out on the GFRP skin, the CS key and the foam materials. Five coupons of each material per test type were tested to determine their mechanical properties. Static tensile (ASTM D3039/D3039M-08 [34]) test was carried out on the GFRP and CS specimens. Static tensile (ASTM C297-04 [35]), compressive (ASTM C365/C365M-05 standard [36]) and shear tests (ASTM C273-00 [37]) were run to determine the material elastic characteristics and strength of the foam. Fig. 1 and Fig. 2 show the test setup of the investigated materials while Table 1 summarizes the mechanical properties extracted from coupons tests.

The tensile stress–strain responses of the GFRP laminate and CS are shown in Fig. 3(a) and (b), respectively. It can be seen that the tensile response of the GFRP laminate are quite non-linear while those of the CS samples appear less non-linear. The moduli of elasticity of the tension test coupons

Fig. 1. Tension test setup: (a) GFRP coupons and (b) CS coupons.