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Flatwise compression and flexural behavior of foam core and polymer pin-reinforced foam core composite sandwich panels

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The behavior of foam core sandwich (FCS) and polymer pin-reinforced foam core sandwich (PRFCS) panels was experimentally explored for flatwise compression and flexural loadings. The FCS and PRFCS panels were made of chopped strand mat glass/polyester as face sheets and polyurethane foam as core material using a vacuum infusion process. The aim of the study is to determine the effect of the polyester pin reinforcement in the foam core when the panels are subjected to flexural and flatwise compression loadings. Moreover, the effects of different loading rates on the flexural response of glass/polyester laminate and both types of the sandwich panels were determined. It was found that by reinforcing the foam core with cylindrical polymer pins, the flatwise compression and flexural properties of panels were increased significantly. Furthermore, it was found that the diameter of polymer pins had a large influence while the loading rate had a moderate influence on the flexural stiffness of both types of the composite sandwich panels.

1. Introduction

Composite sandwich structures are made of two thin and rigid face sheets and a light and thick core material. Due to the advantages of composite sandwich structures such as the high specific strength-to-weight ratio, these structures are widely used in industries such as automotive, aircraft and aerospace, marine and civil industries. In application, these structures are usually subjected to various types of loadings such as compression, bending, and low and high-velocity impact loadings. Due to the difficulties in visually detecting damages under different types of loadings [1], understanding of the mechanical behavior of composite sandwich panels is crucial in predicting their strength.

Various studies have been carried out on damage and failure behavior of composite sandwich panels under compression and three point flexural loadings [2–8]. For example, analytical studies on the collapse mechanism of composite sandwich structures under three-point flexural loading has been carried out by Steves and Fleck [9] where different types of failures in composite sandwich structures with composite face sheets and foam core have been analyzed. Composite sandwich beam with two various boundary conditions, fully clamped and simply supported, under three-point flexural loading has been studied by Tagarielli et al. [10] to determine the collapse modes and simple formulation has been presented. In this study, softening post-yield and hardening behaviors have been demonstrated in the simply supported and fully clamped composite sandwich beam.

Sandwich structures with aluminum foam core under four-point flexural loading have been studied experimentally by Styles et al. [11] and the effect of the foam core thickness on failure modes has been observed for the sandwich structure. Styles et al. found that thick sandwich beam has failed because of core indentation while in thin sandwich beams, they failed due to skin wrinkling and fracture and core cracking and crushing. Composite sandwich beams under two types of flexural loading, flatwise and edgewise flexural loadings, have been studied by Manalo et al. [12]. In this study, composite sandwich beams made of glass fiber-reinforced polymer face sheets and modified phenolic core material under four-point flexural loading have been tested. Manalo et al. found that composite sandwich beam in the edgewise flexural loading could take more loads than in the flatwise position and sandwich beam in the edgewise position had failed according to progressive failure of the face sheets while in the flatwise position, the beams failed due to shear failure of the core. Experimental study on composite sandwich beam made of unidirectional carbon fiber reinforced epoxy resin face sheets and aluminum honeycomb core with adhesive film under four-point flexural loading has been carried out by Daniel and Abot [13]. In this study, softening non-linearity and stiffening non-linearity have been observed on the compression and tension side of composite sandwich beam. The static and fatigue behaviors of

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composite sandwich beam made of two types of core material, including balsa wood and PVC foam, have been studied experimentally by Dai and Hahn [14]. The face sheets were quasi-isotropic E-glass non-woven fabric cured in epoxy vinylester resin by using vacuum-assisted resin transfer molding (VARTM) and the beams were loaded under three and four-point flexural loadings.

Debonding and delamination are the most important failures in composite sandwich panels, and these failures are considered in most of the experimental and numerical studies [15]. Different types of sandwich panels such as sandwich panels with shear keys and through-thickness stitched sandwich panels were introduced to improve the mechanical properties against debonding failure [16,17]. Recently, through-thickness stitched foam core sandwich panels were studied and used in industries due to their high-performance [18,19]. For instance, by reinforcing the sandwich panel with z-pins, the flat-wise compressive strength of the sandwich panel increased by 2500% [20]. In these structures, the foam core of the sandwich panel is reinforced with fibers in different methods such as orthogonal weaving, stitching, tufting and z-pinning [21]. Although, through-thickness stitched foam core sandwich panels have high-strength performance the fabrication process of these structures is tedious and needs an extra process that will incur an increase in the fabrication cost [22].

In the present study, the flatwise compression and flexural behaviors of two types of sandwich panels, the foam core sandwich panels (FCS) and polymer pins reinforced foam core sandwich panels (PRFCS) were studied experimentally. Both types of sandwich panels consist of glass fiber reinforced polyester face sheets and high density polyurethane foam core. The core of PRFCS panels was reinforced with cylindrical polymer pins. The effects of reinforcing the foam core with two different diameters of cylindrical polymer pins were studied. In the three-point flexural loading, loading rates of 1 mm/min, 10 mm/min, 100 mm/min and 500 mm/min were used.

2. Polymer pin-reinforced foam core composite sandwich panel

Polymer pin-reinforced foam core composite sandwich (PRFCS) panel is a new type of sandwich panel where the foam core is reinforced with circular polymer pins which also rigidly connect the top and bottom face sheets. A schematic of PRFCS panel is illustrated in Fig. 1. The polymer pins function to prevent the low strength foam-core from crushing and prevent the interface between the face sheets and the foam-core from debonding and delamination. The polymer pins are made of the same polymer that is used in the face sheets' matrix. The advantages of PRFCS panel over the other types of sandwich panels are listed below:

1. The fabrication takes place in one step. Therefore, the face sheets, foam core and the polymer columns are integrated into one construction.
2. The polymer pins rigidly joined the top and bottom face sheets of the panel and improve the resistance of the face sheets and foam core from debonding and increasing the interface strength between the foam core and the face sheets.

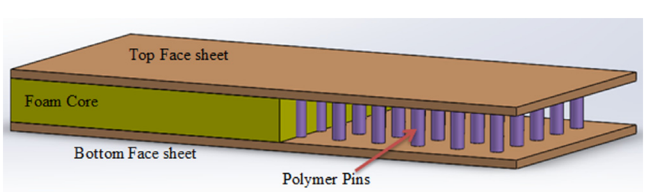

Fig. 1. Schematic of PRFCS panel (foam core partially removed to show pins).

3. Material

The face sheets of the sandwich panels are made of three layers of chopped strand mat glass fiber (600 g) and polyester resin and the foam core is a high density (139.13 kg/m^3) polyurethane foam. The face sheets thickness is 1 ± 0.1 mm and the core thickness is 11.5 mm. The tensile, three-point flexural and flatwise compression tests were carried out at constant loading rate of 1 mm/min to determine the tensile and the flexural properties of glass/polyester laminate and the compression property of foam core material, respectively. The support span length for the three-point flexural tests of chopped strand mat glass fiber/polyester laminate was set to be 32 mm, which is 16 times the total thickness of specimens. The details of specimens for experimental tests to determine the mechanical properties of materials are listed in Table 1.

Figs. 2 and 3 show the stress–strain curves of the tensile tests and flexural stress–deflection curves of three-point flexural tests of chopped strand mat glass/polyester laminate, respectively. Fig. 4 shows the compressive stress–strain response of polyurethane foam core subjected to flatwise compression loading. The mechanical properties of chopped strand mat glass fiber/polyester laminate such as Young's modulus E, Poisson's ratio ν, failure stress σ_F, failure strain ε_F, flexural failure stress σ_F^f and the ultimate strength are listed in Table 2. Using ASTM Standard for flatwise compression test, the ultimate strength of foam core was determined. From Fig. 4, the value is calculated to be 1.297 MPa.

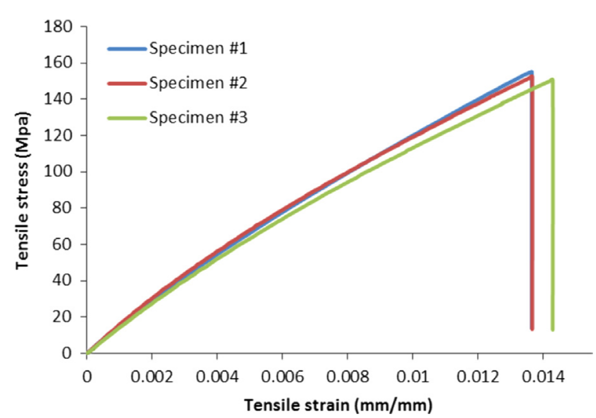

Fig. 2. The stress–strain curves of glass/polyester laminate.

Table 1
The details of specimens for tests to determine the mechanical properties of materials.

Specimens	Type of test	Type of specimen	Dimensions
Glass/polyester laminate	Tensile	Dog bone	15 mm × 100 mm (gauge length) × 2.1 mm
Glass/polyester laminate	Flexural	Rectangular	15 mm × 100 mm
Polyurethane foam core	Flatwise compression	Square	50 mm × 50 mm