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Numerical modeling and experimental validation of axially loaded slender sandwich panels with soft core and various rib configurations

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ABSTRACT

In this paper experimental and analytical investigations of axially loaded sandwich panels are presented. Large scale slender panels with and without ribs were tested. A robust analytical model applicable to panels of various slenderness ratios was developed. It accounts for geometric non-linearity through a rigorous P-Delta analysis, including the initial out-of-straightness profile and end eccentricities. The excessive shear deformation of the soft core and its effect on the overall stiffness and global buckling is accounted for. Additionally, the model detects localized skin wrinkling or crushing. The model showed reasonable agreement, within ±20%, with test results for strength and stiffness and was used in a parametric study. It was shown that the addition of a longitudinal rib connecting the skins at mid-width resulted in 180% increase in axial strength, by changing failure mode from skin wrinkling to global buckling. Adding longitudinal external ribs to the internal one changed failure mode to skin crushing and increased stiffness by 40% but did not enhance strength. Axial stiffness and strength also increased as skins or ribs became thicker, or their Young's modulus increased, or as core shear modulus increased, however, failure mode varied depending on length. As the amplitude of out-of-straightness increased, failure load always reduced, weather governed by global buckling or skin wrinkling.

1. Introduction

Sandwich panels provide an effective structural system that takes advantage of materials with high strength-to-weight ratios for exterior thin skins spaced apart by a low density core material [5]. As explained by Hermann et al. [11], the concept of sandwich technology had initially been used in construction as far back as 1849 but most of the innovations over the past century have occurred within the aviation industry. A common practical sandwich panels system consists of cellular polyurethane cores and glass fiber reinforced polymer (GFRP) skins [22]. For structural engineering applications, Sharaf and Fam [19] developed and tested six $2500 \times 660 \times 80$ mm GFRP–polyurethane specimens for out-of-plane bending. In these specimens, six distinct configurations of internal and external ribs were investigated and compared, in terms of the effect on flexural strength and stiffness. The work was extended to develop and test under simulated wind loading large ($9144 \times 2438 \times 78$ mm) sandwich cladding panels for buildings [20]. Mathieson and Fam [17] looked into the potential of using sandwich panels as load-bearing walls through an investigation of the axial loading behavior of small scale sandwich specimens with various slenderness ratios.

The mechanics of sandwich panels and general performance theories have been developed, including specific failure modes that are unique to this system [1,3]. One critical failure mode involves a localized skin instability, referred to as wrinkling, due to the nature of the soft core. A general unified theory for predicting this mode was introduced by Benson and Mayers [2]. Global instability, or buckling, is another potential failure mode for axially loaded slender sandwich panels. Several studies have looked into the interactions between global buckling and wrinkling, including the failure of the core interface with the skins [12,15,14,25]. As shown by Dawe and Yuan [6], the soft cores of sandwich panels result in significant shear displacement which contributes to both out-of-plane bending and buckling. Analytical and finite element models of sandwich panels have been developed and successfully predicted localized wrinkling of skins [10,9,21].

This paper presents experimental and numerical investigations of axially loaded sandwich panels. The experimental component investigates large scale slender sandwich panels with and without ribs of various configurations. A new numerical model is also developed. The model is applicable to panels with various

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slenderness ratios and rib configurations, and accounts for geometric non-linearity through a rigorous P-Delta analysis. The model accounts for geometric imperfection by considering the initial out-of-straightness profile of any shape and the end eccentricities. The excessive shear deformation of the soft core and its effect on the overall stiffness and global buckling of the panel is accounted for. Additionally, the model detects localized skin wrinkling or crushing. Results of the experimental program and from literature are used to verify the new model. A comprehensive parametric study is also carried out using the model.

2. Experimental program

This section provides a summary of the experimental program used to validate the numerical model, including material properties, test specimens and parameters, test setup and instrumentation, and summary of test results.

2.1. Material properties

The core of the sandwich panels tested is composed of 75 mm thick Polyurethane foam panels, fabricated from Corafoam U20 closed-cell polyurethane foam with a density of 32 kg/m^3. The stress–strain curves of this foam under axial tension and compression and shear loading [19] are shown in Fig. 1(a and b). The Young's modulus in compression and shear modulus are 1.65 MPa and 2.76 MPa, respectively. The Poisson's ratio is −0.7, which is not unusual for this type of closed-cell foam [16] as a result of the change in micro-structure from conventional honeycomb to a so-called 'auxetic' that stretches or contracts in both directions. The 1.6 mm thick GFRP skin was fabricated from 54 oz. 3 weave E-glass 2022 silane sized and CoPoxy 4281A resin with Copoxy 4284 hardener. The stress–strain curves of the skin under axial and shear loading [19] are shown in Fig. 1(c and d). The Young's modulus of GFRP in compression is 33.4 GPa and its shear modulus is 1.54 GPa. The manufacturer reported a 2.4 GPa Young's modulus for the epoxy.

2.2. Test specimens and parameters

2.2.1. Specimens with variable rib configurations

In this study, six similar length large specimens (AX1–AX6) with a single GFRP layer for skins were fabricated, each with a distinct rib configuration as shown in Fig. 2(a) and summarized in Table 1. Specimen AX1 is a 2440 × 633 × 78 mm section and has no ribs. AX2 is 2510 × 654 × 78 mm with a central longitudinal double layered rib running its entire length. The rib consists of two back-to-back C-shape GFRP layers (detail 'B' in Fig. 2(a)). Similarly, AX3 is 2520 × 654 × 78 mm, with a central longitudinal rib but also has a mid-length transverse rib. AX4 is 2560 × 689 × 78 mm with no internal ribs but has a single layered exterior rib all around (detail 'C' in Fig. 2(a)). AX5 and AX6 are 2280 × 689 × 78 mm long, with AX5 having longitudinal internal and exterior ribs while AX6 is similar but with an additional transverse internal rib.

2.2.2. Specimens with variable slenderness ratio

These specimens were tested in a different study and are presented here as they will be used as part of the model verification. The specimens had different cross-sectional configurations (Fig. 2(b)), namely single-layered skins, double-layered skins and section with internal rib. The key parameter, however, was the slenderness ratio, where the length varied from 500 to 2400 mm. Details of these tests can be found elsewhere [17].

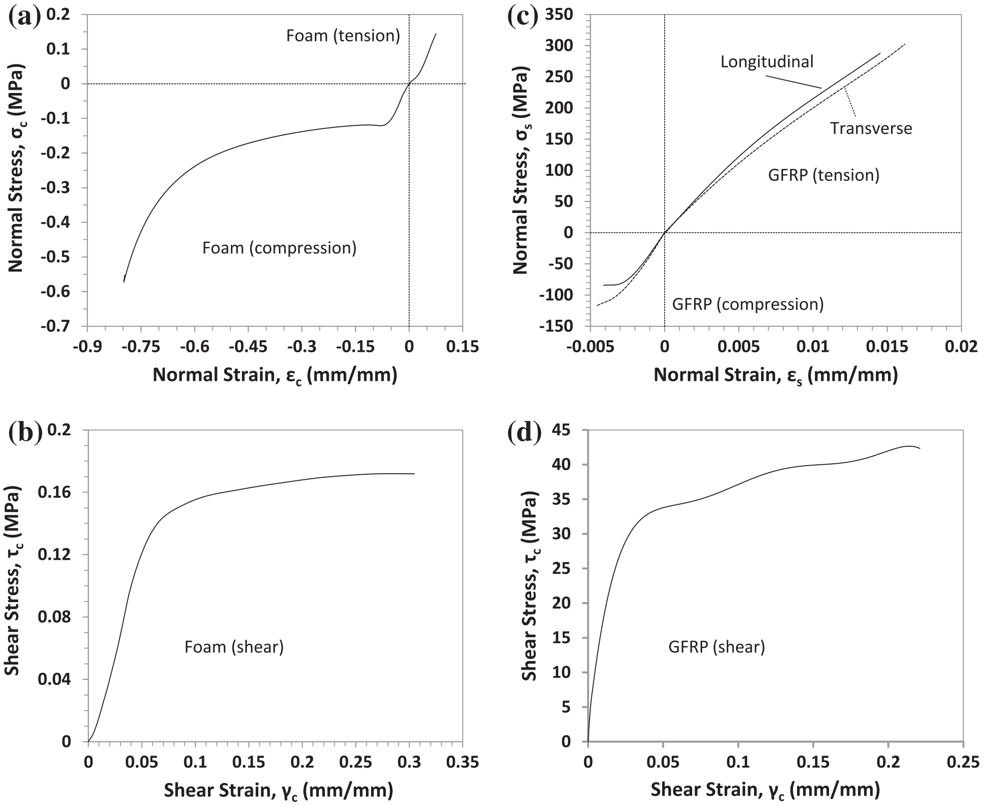

Fig. 1. Stress–strain behavior for polyurethane core under (a) axial stress and (b) in shear, and for GFRP skins/ribs under (c) axial stress and (d) in shear.