Composite Structures 116 (2014) 453–460

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Modeling of axial and shear stresses in multilayer sandwich beams with stiff core layers

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ARTICLE INFO

Article history:
Available online 7 June 2014

Keywords:
Analytical sandwich models
Multilayer sandwich beam
Stiff/rigid cores
Balsa core
Timber core

ABSTRACT

In order to optimize the load-bearing behavior of sandwich structures and adapt it to specific requirements, their core may be composed of layers of different materials with tailored properties. These layers may consist not only of soft foam or honeycomb materials but also comprise stiff materials, e.g. timber, or even very stiff laminates in the case of fiber-reinforced polymer (FRP) materials. In this paper, new analytical models for predicting axial and shear stresses in multilayer sandwich structures composed of stiff core layers and intermediate laminates are presented. The models are based on new formulations for calculating the bending and shear stiffness of multilayer sandwiches. They have been validated by finite element modeling (FEM) and the results from four-point bending experiments on GFRP-balsa sandwich beams with complex core assembly. In contrast to existing models, e.g. the high-order sandwich panel theory (HSAPT), the new models are able to accurately predict axial and shear stresses in stiff cores and intermediate FRP laminate layers.

1. Introduction

Sandwich structures are efficient load-bearing components normally composed of a lightweight core made of structural foam or balsa, which separates two thin face sheets, usually made of metals or fiber-reinforced polymer (FRP) laminates. In order to further optimize these structures and provide tailored designs for specific applications, multilayer sandwiches are developed, which involve variation of the core materials and properties in different layers through the thickness of the sandwich.

Multilayer sandwich structures were developed to increase peeling, impact and wrinkling strengths [1,2] for example. Thin layers of peeling-resistant or impact energy absorbing foam cores were inserted between outer face sheets and inner cores. Complex core assemblies were also used to improve the performance of FRP-balsa sandwich bridge decks [3]. The complex core comprised upper high-density and lower low-density balsa layers, separated by an FRP arch inserted into the high-/low-density core interface. The upper high-density core was also intended to prevent indentation caused by wheel loads. Furthermore, multilayer sandwich structures have been successfully applied in radomes in the aerospace industry [4]. Again foam cores with high impact resistance were used close to the outer face sheet to resist wind and impact loads whiles high insulation foam cores were used close to the inner face sheet subjected to thermal loads.

Analytical models exist to predict the mechanical behavior of multilayer sandwich structures. They are based on Reissner–Hoff's models developed for single-layer core sandwich beams, which assume a plane strain distribution through the thickness. The face sheets resist the bending moments that cause axial in-plane stresses, while the core bears the shear forces that cause out-of-plane shear stresses [5,6]. The first analytical model for multilayer sandwich beams was developed by Little and Liaw using an energy method [4]. The face sheets were modeled as isotropic membrane layers without any bending rigidity while the core layers were assumed to be orthotropic and to only resist out-of-plane shear stresses but not axial stresses. A further assumption was that the core layers exhibited the same shear strain through the core thickness. Using the same energy method and similar assumptions, Little and Liaw's model was extended by Azar [7] to include orthotropic face sheets.

Again based on a similar energy method, Kao and Ross [8] established a model that is able to attribute, depending on the shear moduli, different shear strains to the individual core layers. Furthermore, the model can also take the bending rigidity of the face sheets into account. They showed that, compared to their model, Little and Liaw's model resulted in a 79% underestimation of the shear strain of the weak core of a sandwich with two core

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http://dx.doi.org/10.1016/j.compstruct.2014.05.049
0263-8223/

layers with a shear stiffness ratio of 10. Kao and Ross' model was then extended by Khatua and Cheung [9] to include the influence of face sheet thickness on the shear strains of the core layers. This new model was validated by FEM for arbitrary isotropic and orthotropic face sheets and core properties.

Frostig and Rabinovitch [10] used a different approach and developed two new multilayer models based on the high-order sandwich panel theory (HSAPT), one that takes into account only core layers and a second one that enables intermediate "skin" or laminate layers to be placed in between core layers. The models involve the solution of 13 differential equations and were not validated by any other method. The models also take only soft cores into account (assuming a constant shear stress distribution through the thickness) and thus disregard axial deformations and stresses in the cores.

Meanwhile, stiff cores such as balsa and timber are being increasingly used in sandwich structures due to their favorable shear properties and significant contributions to bending stiffness and resistance [11,12]. The balsa core of a glass-FRP (GFRP) sandwich beam bore 18% of the axial force resulting from the bending moment [11]. Furthermore, the maximum shear stress resulting from the correct parabolic distribution exceeded that resulting from a constant distribution by 14%.

None of the existing models for multilayer sandwich structures is able to accurately predict axial and shear stresses in the case of stiff cores. The HSAPT model is also complex, involves considerable computational times and has not yet been validated. This paper thus proposes new analytical models for predicting axial and shear strains and stresses in multilayer sandwich structures composed of stiff cores and intermediate laminates. The models have been validated by both FEM and results from 4-point bending experiments on the GFRP-balsa sandwich beams with complex core assembly described above [3].

2. Experimental work and FEM

The main validation of the analytical models occurred through comparisons with FEM results. However, experimental results from a previous work [3] were also applicable. Multilayer sandwich beams were experimentally investigated. The middle layer in those beams was not plane and parallel to the face sheets but had an arch shape, see details below. Since the arch rise was very small and the axial strain distributions remained plane through the thickness of the beams, the analytical models were also applicable to those beams. Both experimental and FEM results are subsequently presented.

2.1. Experimental beam and material description

Two types of sandwich beams with complex core assemblies were experimentally investigated: (1) beams where an upper, high-density balsa (SB150) core was separated from a lower, low-density balsa (SB50) core by a circular adhesive interface (denominated B-H/L beams), and (2) beams with the same balsa core configuration but with a GFRP arch laminate in the circular high-/low-density balsa core interface (denominated A-G beams), as shown in Fig. 1. In both configurations, the lower face sheets were a 2-mm-thick CFRP layer, while a 2-mm-thick GFRP layer was applied as the upper face sheets. For the arch laminate, a 2-mm-thick GFRP layer was used. The balsa cores were oriented with fibers perpendicular to the face sheets to prevent indentation. The properties of the FRP laminates and balsa materials are given in Tables 1 and 2. Beam length, span and width were 2400 mm, 2000 mm and 180 mm, respectively and the total core height was 100 mm.

2.2. Experimental set-up, instrumentation and measurements

The beams were loaded in a 4-point bending configuration, at the third points of the span, in different loading cycles up to failure; the beam set-up is shown in Fig. 2. Deflections were monitored with linear voltage displacement transducers and axial strains on the face sheets and arch laminates were measured with strain gages. Axial deformations of the core were measured in one section close to the right-hand load, see Fig. 2, using four Omega gages, one in the compression zone, one on each side of the arch or the adhesive interface and another in the tension zone. Shear deformations through the core thickness, including the arch laminate, were measured by five shear strain gages placed 334 mm from the left support. Two beams per configuration were examined.

2.3. Finite element modeling of two beam configurations

Two multilayer sandwich beam configurations were modeled: (1) a sandwich beam with two core layers (denominated ML-1) and (2) the same sandwich beam with an intermediate laminate between the two cores (ML-2). The beams were modeled as simply supported and subjected to the same symmetric four-point bending as the experimental beams, see Fig. 3.

Both sandwich beams had the same dimensions and material configurations as the experimental beams. The only difference concerned the intermediate laminate layer or core interface, which was modeled parallel to the face sheets and not as an arch. To simulate the beam deflections and axial stresses at the mid-span of the B-H/L and A-G beams, the interface of the two cores was placed at 80% of the total core thickness (100 mm), which corresponds to the height of the arch interface/laminate at the mid-span of the beams. The prediction of the shear stresses was done at 334 mm from the left support, selecting the interface at 43% of the total core thickness (height of the arch interface/laminate at this location). In a variant of beam ML-1, the upper SB150 balsa core was subsequently replaced by Douglas fir (Df) to demonstrate the effect of increased core bending stiffness. The mechanical properties of Douglas fir are also listed in Tables 1 and 2.

The two sandwich beams were modeled in 3D by ANSYS v-13 software, using an 8-node layered shell element (shell 99) for the face sheets and intermediate laminate and a 20-node structural solid element (solid 95) for the cores. The common nodes of the shell and solid elements were joined together by applying the Boolean–Glue operation. The face sheets and intermediate laminate were modeled in 8 layers of 0.25-mm thickness each and 100 layers of 1-mm thickness were used for the cores. For the Douglas fir, the fibers were oriented in the beam direction to simulate its orientation as the upper core layer in a GFRP-balsa sandwich bridge deck with complex core assembly, whose fibers are oriented in the bridge direction to increase bending rigidity and shear capacity. Perfect bonding conditions were assumed at the face sheet/core joints as well as at the dissimilar core joints, and hence the adhesive bonds applied at these joints in manufacture were not modeled. The beams were meshed using 11,081 face sheet/laminate and 54,043 core elements. Due to symmetry of the beam structure and loading, only half of the beams were modeled (see Fig. 3) and symmetry boundary conditions were applied at the mid-span cross sections.

Linear elastic simulations were performed for serviceability limit state (SLS) loads at 2×0.95 and 2×1.05 kN for beams ML-1 and ML-2 respectively. The SLS loads were defined at maximum beam deflections of span/500, according to Eurocode-2 part 2 [13].