TESTING AND ANALYSIS OF COMPOSITE SANDWICH BEAMS

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SUMMARY: The objective of this work was to study the behavior of composite sandwich structures and develop simple models to explain this behavior as a function of material, geometric and loading parameters. The scope of the study consists of mechanical characterization of the sandwich constituent materials, i.e., composite facings, honeycomb and foam cores, and adhesive layers; fabrication and testing of sandwich beams in bending; identification and recording of failure mechanisms by direct observation and nondestructive evaluation; and comparison of observed deformation and failure behavior with analytical predictions. The beam facings displayed the characteristic nonlinearities of the composite material used, a softening nonlinearity on the compression side and a stiffening one of the tension side. The linear response of the beam is perfectly described by a simple bending model neglecting the contribution of the core, however, the more pronounced nonlinear behavior requires more accurate characterization of the core and adhesive materials separately, and more refined modeling.

KEYWORDS: Sandwich beams, fabrication, carbon/epoxy composite, honeycomb cores, foam cores, test methods, modeling, nonlinear response, failure mechanisms.

INTRODUCTION

Sandwich construction is of particular interest and widely used in many structures, because the concept is very suitable and amenable to the development of lightweight structures with high in-plane and flexural stiffness. Sandwich panels consist typically of two thin face sheets or facings or skins and a lightweight thicker core. Commonly used materials for facings are composite laminates and metals, while cores are made of metallic and non-metallic honeycombs, cellular foams, balsa wood or trusses. The face sheets are typically bonded to the core with adhesive. The facings carry most of the bending and in plane loads and the core defines the flexural stiffness and out-of-plane shear and compressive behavior. The structural

performance of sandwich panels depends not only on the properties of the skins, but also on those of the core and the adhesive bonding the core to the skins, as well as on the geometrical dimensions of the components. Important issues in sandwich structures are the quality of the structure, the various failure mechanisms that are developed under various loading conditions, effects of nonlinear material behavior and effects of geometric nonlinearities.

A great deal of work has been published on the behavior of sandwich structures in the last few decades. Many analytical and computational models are available to describe the behavior of sandwich beams, panels and shells under different loading conditions. The fundamentals of sandwich construction and reviews of analytical and computational methods are described in recent works by Zenkert [1], Noor et al. [2] and Reddy [3]. Many of the models proposed to date are approximations to the three-dimensional elasticity theory based on assumptions for the displacements, strains and/or stresses through the thickness. The validity of the various approximations depends on the geometry of the beam, properties of the component materials and loading conditions. Most theories assume linear elastic behavior for the component materials and small deflections. However, material and geometric nonlinearities are important issues. In addition to modeling material behavior, the relative motions of the facings must be taken into account in the so-called "multilayer buildup" theory [4,5]. When transverse deflections become of the order of the beam depth nonlinear analyses may be necessary [6]. Several papers have discussed the nonlinear load deflection behavior of sandwich plates [7-9].

The objective of this work is to study experimentally the behavior of composite sandwich beams under pure bending and three-point bending and compare the results with predictions of theoretical models.

EXPERIMENTAL PROCEDURE

The sandwich beam facings were unidirectional carbon/epoxy plates (AS4/3501-6). The facing plates as well as additional plates for material characterization were fabricated by autoclave molding. Uniaxial tensile and compressive tests were conducted primarily in the longitudinal direction in order to obtain the relevant constitutive behavior of the facing material. The longitudinal tensile and compressive stress-strain behavior for the AS4/3501-6 carbon/epoxy is shown in Fig. 1. It can be seen that the material exhibits a characteristic stiffening nonlinearity in tension and softening nonlinearity in compression. One of the core materials used in this study was aluminum honeycomb PAMG 8.1-3/16 001-P-5052 (Plascore Co., 5052 aluminum alloy, 8.1 lb/ft^3 density, 3/16 in. cell size, 0.001 in. foil gauge). The material is highly anisotropic. The in-plane stiffnesses E_1 and E_2 and the out-of-plane stiffness E_3 (along the cell axis) were obtained by means of flexural and pure compression tests. The out-of-plane shear modulus was obtained by means of a rail-shear test. The second core material used was a PVC closed-cell foam (Divinycell H100). The material was tested under tension, compression and shear. The adhesive used to bond the facings to the honeycomb core was FM73M film adhesive (Cytec-Fiberite). It is a 0.050 mm (0.002 in.) thick toughened epoxy layer reinforced with glass fabric. The shear properties of the adhesive were determined by using the Arcan fixture. Some characteristic properties of the sandwich component materials are tabulated in Table 1.

The honeycomb core was 2.54 cm (1 in.) wide and was machined from the 2.54 cm (1 in.) thick sheet along the stiffer (E_1) direction. The 2.54 cm (1 in.) wide composite facings were machined from the unidirectional plates, bonded to the top and bottom faces of the honeycomb

core with FM73 M film adhesive and the assembly was cured under pressure in an oven following the recommended curing cycle for the adhesive. Sandwich beams were also prepared by bonding composite facings to foam cores of 2.54 x 2.54 cm (1 x 1 in.) cross section using a commercially available epoxy adhesive (Hysol EA 9430).

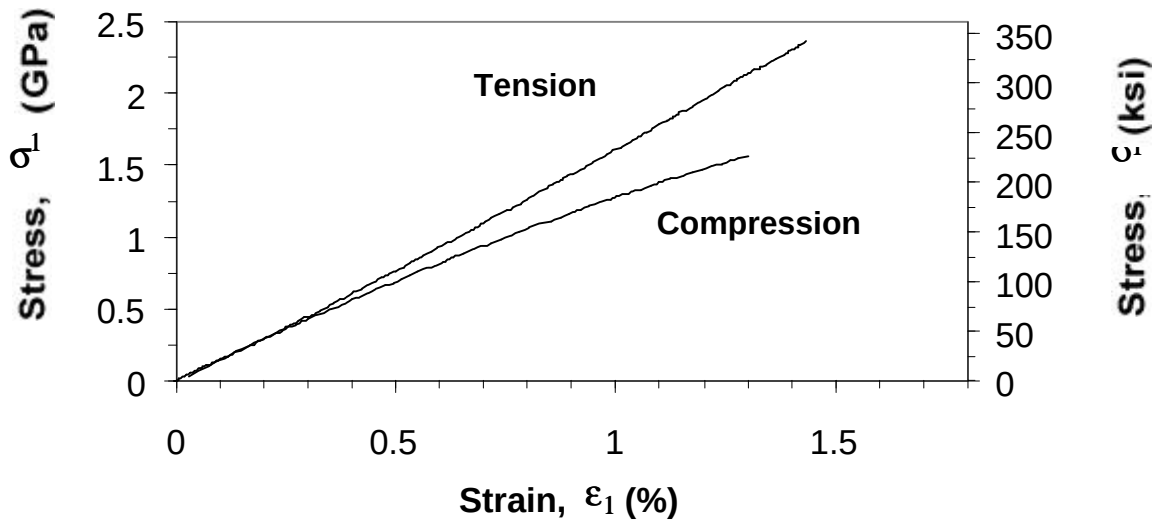

Fig. 1: Longitudinal tensile and compressive stress-strain behavior of AS4/3501-6 unidirectional carbon/epoxy.

Table 1: Characteristic Properties of Sandwich Constituent Materials

	Facing	Honeycomb Core	FM-73 Adhesive	Foam Core
Density, ρ, kg/m^3 (lb / ft^3)	1,620 (102)	129 (8.1)	1,180 (74)	100 (6.0)
Thickness, h, mm (in.)	1.01 (0.040)	25.4 (1.0)	0.05 (0.002)	25.4 (1.0)
Longitudinal Modulus, E_1, MPa (ksi)	147,000 (21,260)	8.27 (1.2)	1,700 (247)	120 (17.5)
Transverse Shear Modulus, G_{13}, MPa (ksi)	7,600 (1,100)	580 (84)	110 (16)	48 (6.9)
Transverse Shear Strength, F_{13}, MPa (ksi)	~ 71 (10.3)	2.6 (0.38)	33 (4.8)	1.6 (0.23)

Beams for four-point flexural testing were 45.7 cm (18 in.) long. Because of the low shear strength of the core, shear damage occurred early in the core near the points of load application. In order to prevent premature failures under the loads and to insure failure in the pure bending section, the outer core sections subjected to shear were reinforced by filling the cells with epoxy. Better results were obtained when this cell reinforcement was tapered off gradually into the pure bending section.

Strains on the outer surfaces of the facings as well as on the inner surfaces, at the interface with the adhesive bond, were recorded with strain gages. Most of the gages were oriented along the axis of the beam, but some were mounted in the transverse direction to record transverse strains. The deflection of the beams was measured with a displacement transducer (LVDT) and also monitored with a coarse moiré grating (31 lines/cm, 80 lines/in.). The displacement

field in the core was recorded with a finer moiré grating of 118 lines/cm (300 lines/in.). Before applying the moiré gratings, the lateral surface of the core was coated with a white silicone rubber layer to make the surface smooth and reflective.

Sandwich beams were loaded under four-point and three-point flexure in a servohydraulic machine, while recording load, strain gage, moiré and LVDT data. All specimens were loaded to failure. The four-point bending tests produced compressive facing failures at strains of over 1.5%. The three-point bending tests were carried out until core failure occurred.

RESULTS

Beams under Four-Point Bending

The applied bending moment was plotted versus the outer surface longitudinal strains for a beam with honeycomb core under four-point bending in Fig. 2. The same type of stiffening and softening nonlinearities observed before for the facing materials are seen here. Failure was governed by the compressive strength of the facing, which in this case reached a value of 1930 MPa (280 ksi), higher than any recorded value for this material under direct compression. The ultimate compressive strain recorded was 1.6%.

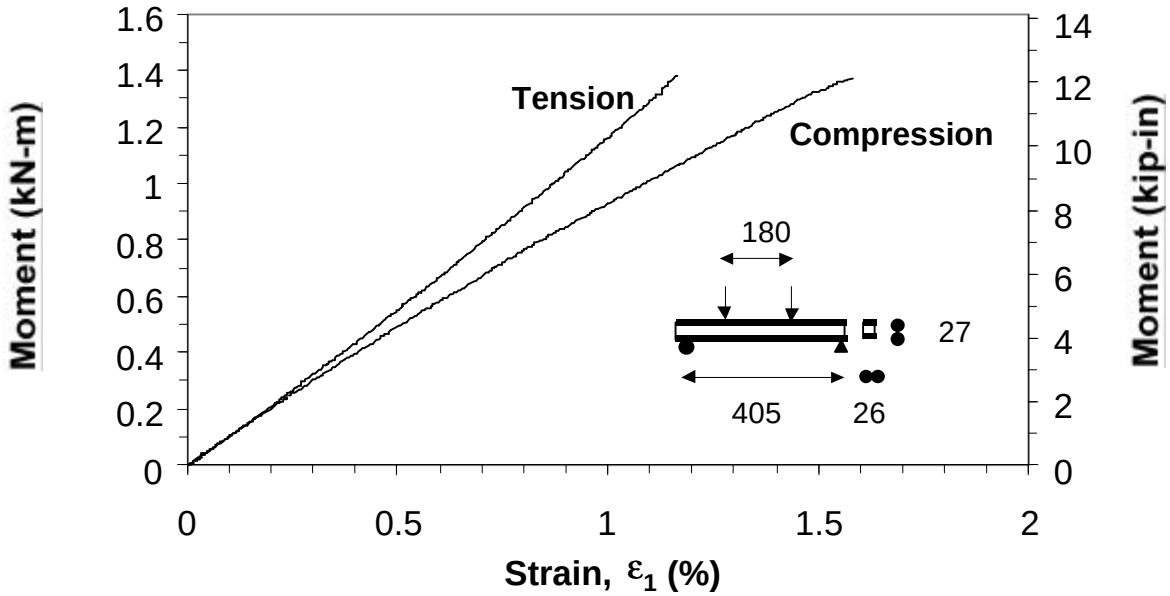

Fig 2: Applied moment versus longitudinal strains for sandwich beam with honeycomb core under four-point bending.

Before comparing the experimental results with available models, the variation of the longitudinal strain through the facing thickness was investigated. Results from another test in Figs. 3 and 4 show the variation with applied moment of longitudinal strains on the outer and inner surfaces of the facings. It is seen that these strains are not constant through the thickness of the facing. Analysis of the data indicates that the inner surface strains are between 3.5 and 4.2% lower (in absolute terms) than the corresponding outer surface strains. A linear strain variation through the entire beam section would imply strain differences of 4%.

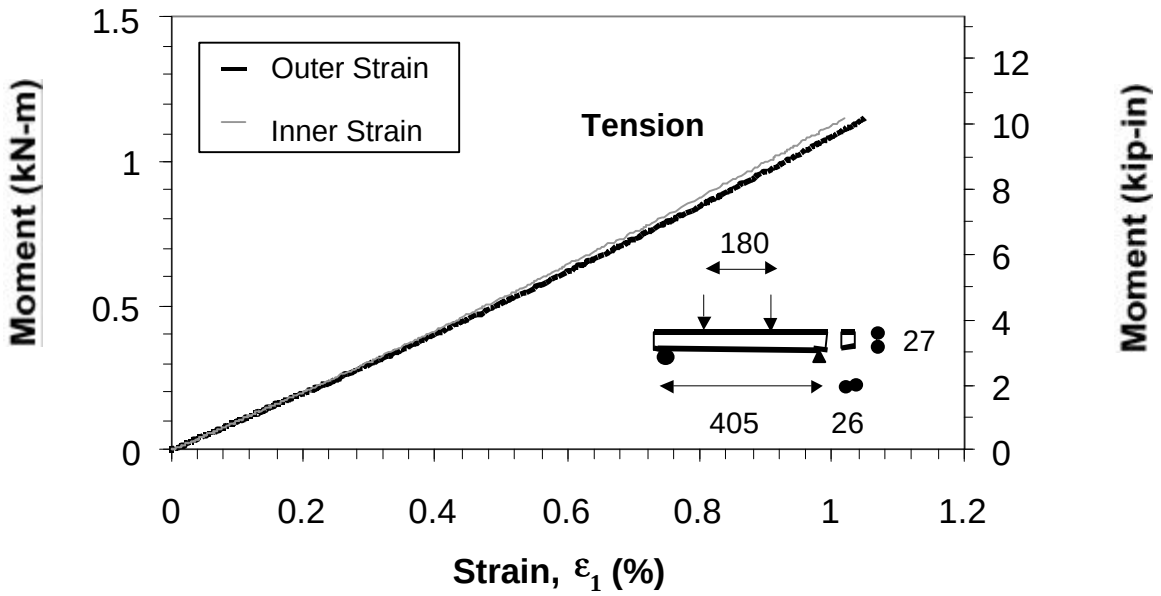

Fig. 3: Applied moment versus longitudinal strains on surfaces of tension facing of sandwich beam under four-point bending.

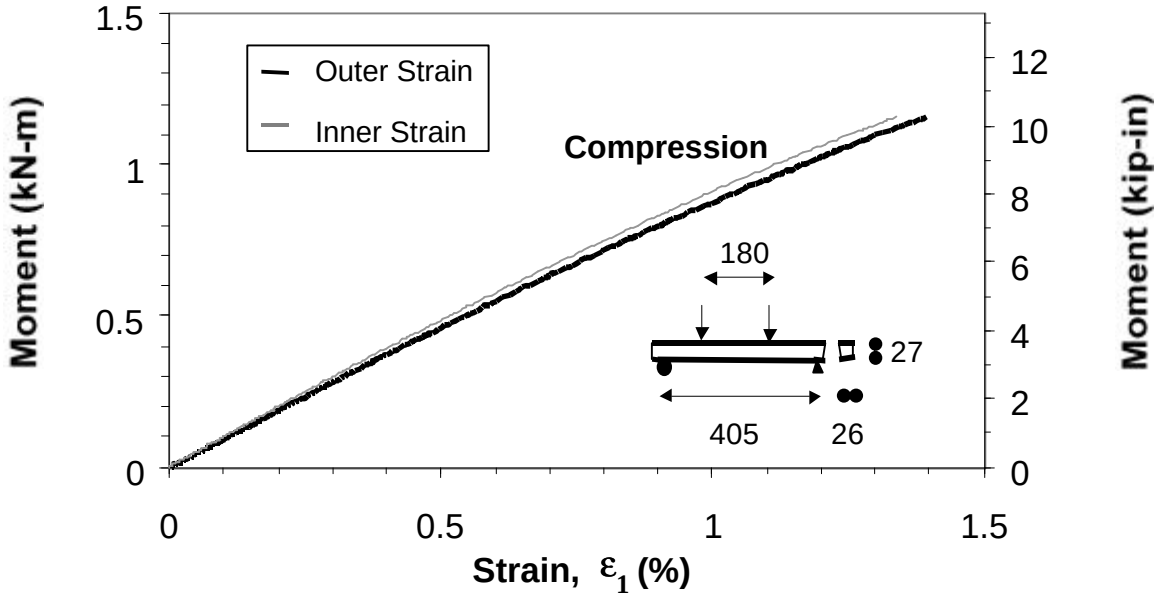

Fig. 4: Applied moment versus longitudinal strains on surfaces of compression facing of sandwich beam under four-point bending.

The strain field in the core was investigated by the moiré technique discussed before. A moiré fringe pattern corresponding to longitudinal displacements in the core is shown in Fig. 5. A linear strain variation through the thickness in the pure bending zone would imply the following form for the strain and displacement

$$\varepsilon_1(z) = cz = \frac{\partial u}{\partial x} \tag{1}$$

$$u(x,z) = cxz \tag{2}$$

since u (0,z) = 0 (along vertical axis of symmetry)

The moiré fringes, being loci of equal displacements, do indeed have the form of hyperbolas and are equidistant along any horizontal line. Furthermore, there is evidence that the neutral axis has shifted toward the tension side because of the different nonlinearities of the tension and compression facings.

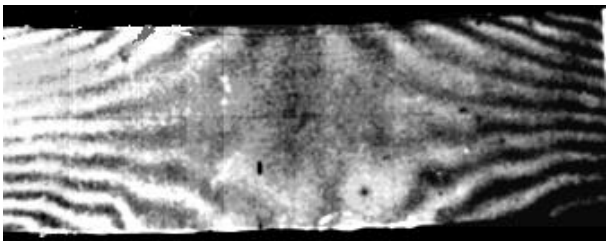

Fig. 5: Moire fringe pattern in the core corresponding to longitudinal displacements (12 lines/mm; 300 lines/in.)

Beams under Three-Point Bending

Under three-point bending and without any special core reinforcement, all beams (with honeycomb core) failed early due to shear crimping of the core. The failure load, being twice the shear force, remained nearly constant for varying span lengths. This means that as the span length decreases, the applied maximum moment, and thereby the maximum facing strains, at failure decrease (Fig. 6). The results also indicate that even in cases of increased shear loading of the core, the bending moment is carried almost entirely by the facings.

Beams with foam cores were tested under three-point bending and strains and deflections were recorded. Figure 7 shows load-deflection curves for two cases. In the cases recorded, where the facing sheets were 8 plies and 4 plies thick (1mm and 0.5mm thick, respectively) the beams failed by local indentation and crushing of the core under the applied load. In this case, failure is not governed by the shear strength of the core, but by a combination of flexural stiffness of the facing and compressive strength of the core. A finite element analysis is in progress to evaluate the behavior of such beams as a function of material and geometric parameters.

Modeling

The objective of the modeling was to predict the relationship between applied loading (moment) and stresses or strains in the sandwich beams, based on the properties and dimensions of the components of the beam. Referring to the schematic of a sandwich beam in Fig. 8, the neutral axis is located at a distance.

$$e = \frac{E_{fc} h_f d + E_c h_c (h_c + h_f)/2}{(E_{ft} + E_{fc}) h_f + E_c h_c} \qquad (3)$$

and for a weak core, $E_c << E_{ft}, E_{fc}$,

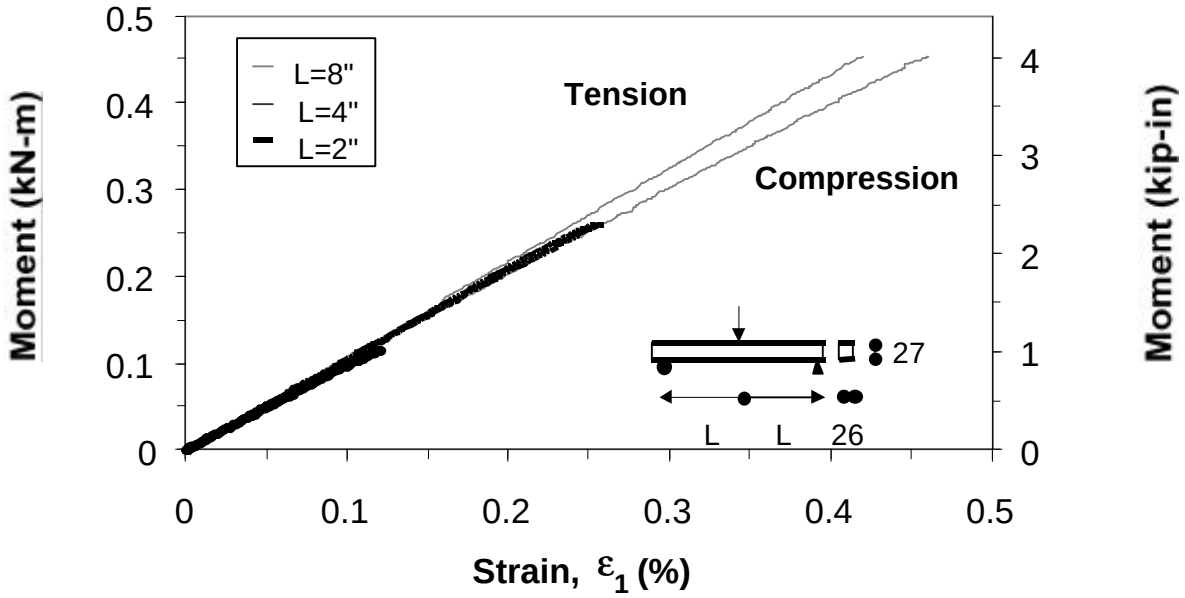

Fig. 6: Applied moment versus maximum facing strain for beams of different span length under three-point bending.

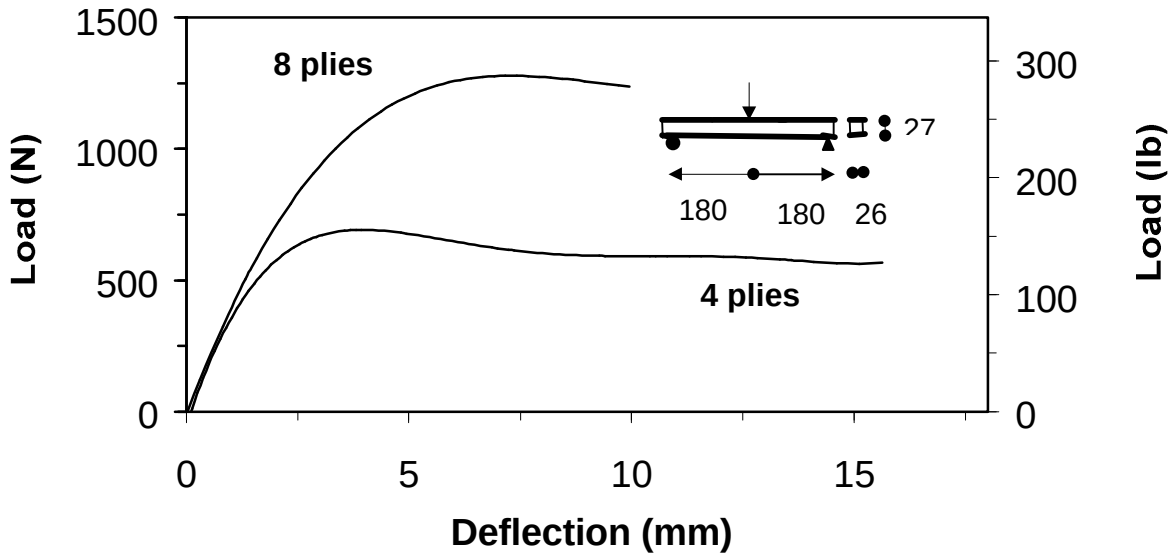

Fig. 7: Applied load versus deflection for beams with foam cores and two facing thicknesses.

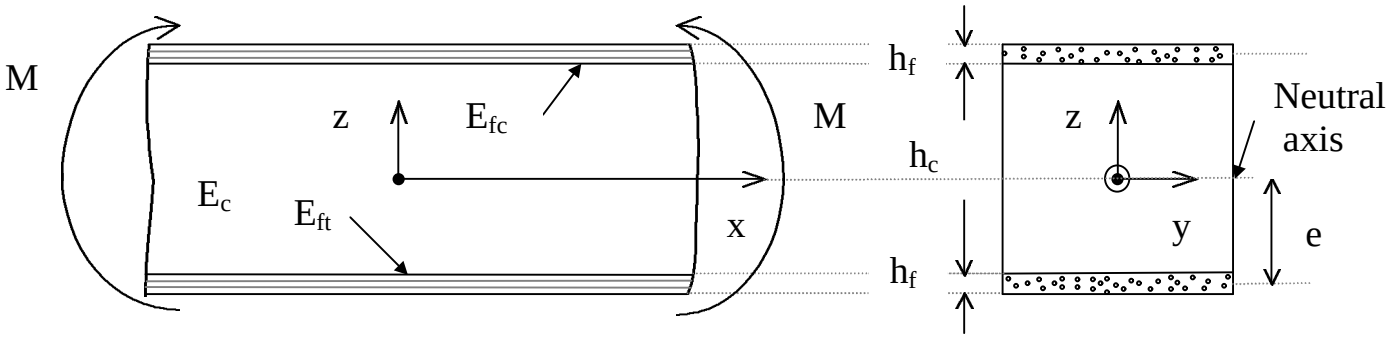

Fig. 8: Schematic of sandwich beam.

$$e \cong \frac{E_{fc} d}{(E_{ft} + E_{fc}) h_f} \tag{4}$$

where

$$d = h_c + h_f$$

The bending stiffness for a weak core is

$$D = \frac{h_f^3}{12} (E_{ft} + E_{fc}) + \frac{E_{ft} E_{fc} h_f d^2}{E_{ft} + E_{fc}}$$

(5)

For thin facings, $h_f << h_c$ we have

$$D \cong \frac{E_{ft} E_{fc} h_f d^2}{E_{ft} + E_{fc}} \tag{6}$$

The normal stresses in the facings and core are

$$(\sigma_{ft}, \sigma_{fc}, \sigma_c) = -\frac{Mz}{D} (E_{ft}, E_{fc}, E_c) \tag{7}$$

For a weak core and thin facings

$$\sigma_{ft} = -\sigma_{fc} \cong \frac{M}{db\, h_f}$$

where b = width of beam

The experimentally obtained stress-strain relationships of the facing material in tension and compression and that of the honeycomb core were used to obtain moment-strain relations. Different cases/assumptions were considered in modeling the sandwich beams tested under pure bending. The first case where a linear variation of strain through the thickness is assumed with a neutral axis through the centroid of the cross section is only valid in the linear range of the facing material. At higher loads, the nonlinear response of the facings must be considered, although other simplifying assumptions can be made. For example, the core contribution could be neglected since its modulus is much smaller than the facing modulus $(E_c << E_f)$. The strain, and hence the stress, in the facings can be assumed to vary linearly or to be constant through the facing thickness. The latter assumption is valid when the facing thickness is much smaller than the core thickness $(h_f << h_c)$. In the present case two models were implemented, one by assuming linear variation of strain through the facing thickness and the other by assuming a constant strain through the facing thickness. In both models the core contribution was neglected. The nonlinear behavior of the facing material was considered in an incremental computational scheme. Results are plotted in Fig. 9 and compared with experimental moment-strain results. It appears that the assumption of constant strain gives better agreement with experimental results. The agreement is satisfactory in general. The small discrepancies observed are not attributed to the model but rather to the difficulty in obtaining reliable stress-strain curves in direct longitudinal compression.

The contribution of the core to the moment-strain relations was found to be negligible. The effect of core modulus was investigated using a model with the assumption of constant strain through the facing thickness. Results are shown in Fig. 10 for the compression and facing. Similar results were obtained for the tension facing. It appears that the influence of the core is not noticeable until its stiffness is approximately 1/200 times the facing modulus.

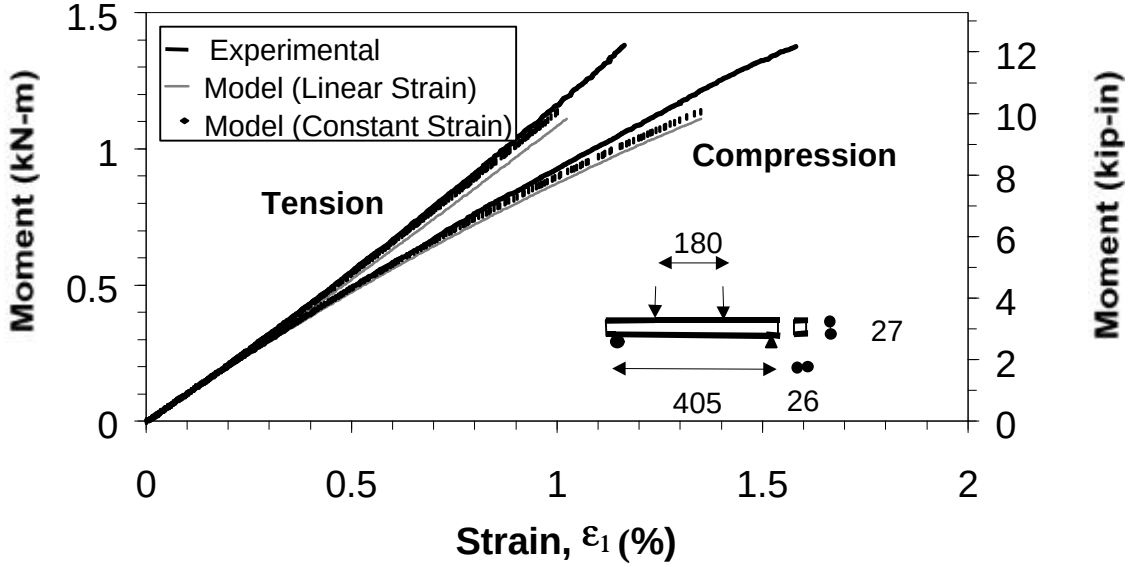

Fig. 9: Experimental and predicted moment-strain curves for two facings of composite sandwich beam under four-point bending.

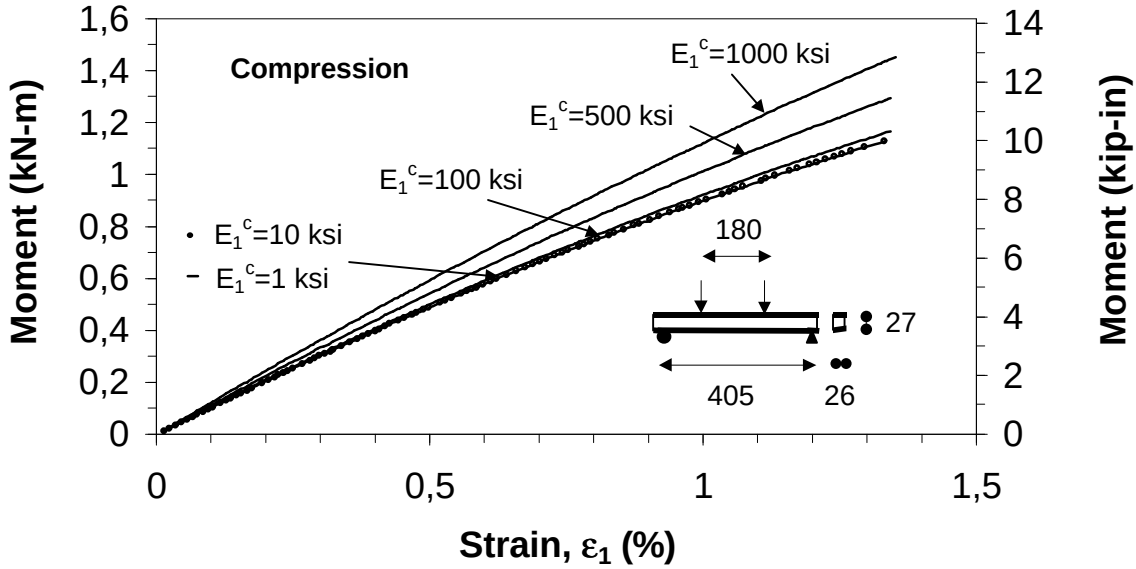

Fig. 10: Effect of core modulus on the moment-strain relationship for sandwich beam under four-point bending (compression facing).

SUMMARY AND CONCLUSIONS

An experimental study was conducted on the behavior of composite sandwich beams under four-point and three-point bending. The sandwich beams were prepared with unidirectional carbon/epoxy facings and aluminum honeycomb or foam cores. Strains in the facings and the core were measured with strain gages and moiré gratings, respectively. The bending behavior of the beams, whether loaded under four-point or three-point bending, is governed by the facings. Therefore, the moment-strain relations for the facings display the same type of nonlinear behavior as the composite material itself, i.e., a stiffening nonlinearity in tension and a softening nonlinearity in compression. A linear variation in strain through the thickness was determined in both core and skins. The contribution of the most widely used cores to the

bending stiffness can be neglected. In the case of pure bending, failure takes place on the compressive facing of the beam where the ultimate compressive stress and strain can reach values higher than any recorded for the composite material under direct compression. When shear is present, failure of the honeycomb sandwich beam is governed by the low shear strength of the core, 2415 kPa (350 psi) for the honeycomb core used here. In the case of beams with foam cores, indentation failures under the load are common and are controlled by the flexural stiffness of the facing and compressive strength of the core. Experimental results were in good agreement with predictions of simple models assuming the facings to behave like membranes and neglecting the contribution of the core, but accounting for the nonlinear behavior of the facings.

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