Failure mode maps for honeycomb sandwich panels

A. Petras, M.P.F. Sutcliffe *

Cambridge University, Engineering Department, Trumpington Street, Cambridge CB2 1PZ, UK

Abstract

Failure modes for sandwich beams of GFRP laminate skins and Nomex honeycomb core are investigated. Theoretical models using honeycomb mechanics and classical beam theory are described. A failure mode map for loading under 3-point bending is constructed, showing the dependence of failure mode and load on the ratio of skin thickness to span length and honeycomb relative density. Beam specimens are tested in 3-point bending. The experimental data agree satisfactorily with the theoretical predictions. The effect of honeycomb direction is also examined. The concept of a failure mode map is extended to give a useful design tool for sandwich panels manufacturers and their customers. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Honeycomb sandwich panels; Failure mode maps

Nomenclature

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* Corresponding author. Tel.: 0044-01223-332996; 0044-01223-332662; e-mail: mpfs@eng.cam.ac.uk

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1. Introduction

Sandwich panels are made of two stiff, strong skins separated by a lightweight core (Fig. 1). By separating the skins in this way, the strength and stiffness of the structure is increased with little increase in weight. Thus sandwich panels are popular in high performance applications where weight must be kept to a minimum, for example aeronautical structures, high-speed marine craft and racing cars. In the most weight critical applications, composite materials are used for the skins; cheaper alternatives such as aluminium alloy, steel or plywood are also commonly used. Materials used for cores include polymers, aluminium, wood and composites. To minimise weight these are used in the form of foams, honeycombs or with a corrugated construction. Nomex, the core which this paper focuses on, is a widely used honeycomb material manufactured by dipping a paper honeycomb substrate into phenolic resin to build up the walls of the honeycomb. As well as mechanical requirements, core materials may also be selected based on their fire-resistance or thermal properties.

Sandwich panels will have stiffness and strength criteria to meet. The stiffness of honeycomb sandwich panels is easy to predict, but it remains difficult to estimate the strength. Typical modes of failure are face yielding, face wrinkling, intra-cell dimpling, core shear or local indentation (where the load is applied to the panel). These failure modes are discussed in greater detail in Section 2. The critical failure mode and the corresponding failure load depend on the properties of the face and core materials, on the geometry of the structure and on the loading arrangement. A comprehensive introduction to the subject of sandwich construction and the development of theoretical analyses up to 1965 is given by Allen [1], updated by Zenkert [2]. Holt and Webber [3] summarise recent developments and analyse the elastic behaviour of honeycomb sandwich beams, assuming linear elastic behaviour for the skin and a rigid core. Mechanical, thermal, and hygroscopic loading on a sandwich beam with a honeycomb core and laminated facings are included by reference [4]. Failure mode maps have been derived by various authors for sandwich panels with flexible cores [5–7]. These authors have been particularly concerned with beams with ductile foam cores, making appropriate assumptions about the elastic and plastic behaviour of the core and skin. However, there appears to be little work on failure of panels with honeycomb cores. The skins behave in a relatively simple manner, but the mechanical modelling of the core material, particularly for foams or honeycombs, is less straightforward. The response of the core to shear loading from the skins or loading normal to the plane of skins is required. The behaviour depends both on the materials used in the core and on the core relative density, the ratio of the core density to that of the solid material constituting the core. Gibson and Ashby [8] give a thorough overview of the literature on cellular materials, quoting many results for foam cores. Zhang [9] and Ashby [10] model the elastic and collapse behaviour for honeycomb materials under shear and out-of-plane compression. Their models agree well with experiments that they make on a wide range of Nomex honeycombs. Shi et al. [11] and Grediac [12] model the transverse shear modulus of a honeycomb core.

In this paper we consider loading under 3-point bending of a sandwich panel made with a brittle honeycomb and brittle skin. We apply the analysis framework and failure mode map technique used by Triantafillou and Gibson [7] for ductile foam cores and ductile skin materials. In Section 2 we review beam theory for sandwich panels. Section 3 describes existing work on honeycomb mechanics. By combining the analysis for sandwich beams with the honeycomb mechanics, we derive in Section 3 failure loads for the various failure mechanisms. This information is used in Section 3.1 to draw up failure mode maps, in which the mechanisms of failure and the corresponding failure loads are plotted as a function of the core relative density and skin thickness/span ratio. Theoretical results are
illustrated using the commercially-popular combination of laminated glass fibre reinforced plastic (GFRP) skins and Nomex core. Theory is compared in Section 4 with experiments on sandwich panels of various core relative densities and skin thickness/span ratios.

2. Beam theory for sandwich panels

In this section we outline the elastic analysis of sandwich beams in 3-point bending. This will be used to evaluate the stresses in the core or skin and hence the failure loads due to the various mechanisms. Consider a simply supported sandwich beam of span \( L \) and width \( b \) loaded in 3-point bending with a central load \( W \) per unit width as illustrated in Fig. 2. The skins each have thickness \( t \) and are separated by a thick layer of honeycomb core of thickness \( c \).

We assume that the skins remain firmly bonded to the core, that the beam bends in a cylindrical manner with no curvature in the \( yz \)-plane and that cross-sections remains plane and perpendicular to the longitudinal axis of the beam. The flexural rigidity \( D \) of the sandwich beam is then given by

\[
D = \frac{E_f b t^3}{6} + \frac{E_f b t d^2}{2} + \frac{E_c b c^3}{12},
\]

where \( d \) is the distance between the midplanes of the upper and bottom skins. \( E_f \) and \( E_c \) are the in-plane Young's moduli of the skin and core respectively for loading in the \( x \) direction (along the axis of the beam). Subscripts 'f' and 'c' denote the face material and the honeycomb core respectively. Subscript 's' is used in later expressions for the solid material from which the honeycomb is made. The three terms on the right hand side of Eq. (1) correspond to bending of the skins about their centroidal axes, bending of the skins about the centroid of the whole beam, and bending of the core, respectively. We can simplify this equation by assuming that bending of the skins about the centroid of the beam is the dominant term. The contributions of the first and third terms amount to less than 1% of this when

\[
d > 5.77 \quad \text{and} \quad \frac{E_f}{E_c} \frac{t}{c} \left( \frac{d}{c} \right)^2 > 16.7,
\]

respectively, so that Eq. (1) becomes

\[
D = \frac{E_f b t d^2}{2} = E_f I,
\]

where \( I \) is second moment of area of the cross-section of the sandwich beam. With 3-point bending the maximum bending moment \( M \) is at the mid-span and the corresponding maximum stress \( \sigma_f \) in the skins is given by

\[
\sigma_f = \frac{M E_f}{d} \frac{d}{4t} = \frac{W L}{4t^2},
\]

However, the above theoretical model neglects the effect of shear deflection in the core, which becomes significant for low density cores. Inclusion of this effect also allows a prediction of observed differences in beam strength for different orientations of the honeycomb ribbon (see Section 2.3 for further details). For the above reasons we follow the suggestion of Allen [1] for the maximum axial stresses in the faces

\[
\sigma_f = \frac{W b L}{4} \left( \frac{c + 2t}{2L} + \frac{W L}{4} \frac{t}{2L} \frac{1}{\theta} \right),
\]

where

\[
\theta = \frac{L}{c} \left[ \frac{G_{ax} \frac{2E_f}{t} \left( 1 + \frac{3d^2}{c^2} \right)^{1/2}}{t} \right],
\]

\[
I = \frac{b c^3}{6} + \frac{b t d^2}{2}, \quad I_f = \frac{b t^3}{6},
\]

\( G_{ax} \) is the out-of-plane shear modulus of the core, \( I \) is the second moment of area of the sandwich with respect to its neutral axis and \( I_f \) is the second moment of area of the faceplates with respect to their own centroidal axes. \(^2\) Eq. (6) shows that \( \theta \) depends on the relative stiffness of the skin and the core. Finally Eq. (5) gives

\[
W = 4 \sigma_f \frac{t}{L},
\]

where

\[
\xi = \frac{t^5/9 + t^3 d^2/3}{ht^3 (\theta - 1) + t^3 d^2/3 + t^2 d^2}.
\]

As the span length \( L \) or the core shear stiffness \( G_{ax} \) approach infinity, Eq. (7) tends to the simple beam model Eq. (4). In the case study presented in Section 3.1, maximum deviations from the simple beam model due

\(^2\) Note that \( I_f \) is not negligible in this approach.
to the finite thickness of the skins and the effect of finite shear stiffness in the core amount to a maximum of 26%.

2.1. Skin failure

Section 2 gives an expression for the maximum stress $\sigma_{fs}$ in the skins. This can be used to predict beam failure due to the skin failure modes of face yielding, intra-cell dimpling or face wrinkling, as illustrated in Fig. 3.

2.1.1. Face yielding

Failure occurs in the top skin due to face yielding when the axial stress in either of the skins (Eq. (5)) reaches the in-plane strength $\sigma_{fy}$ of the face material for loading along the beam axis,

$$\sigma_{fs} = \sigma_{fy}. \quad (9)$$

It is assumed that the skin behaves in a brittle manner. With a symmetrical beam the stress is the same in the tension and compression faces. For composite face materials the compressive face is generally the critical one.

2.1.2. Intra-cell dimpling

A sandwich with a honeycomb core may fail by buckling of the face where it is unsupported by the walls of the honeycomb (Fig. 3(b)). Simple elastic plate buckling theory can be used to derive an expression for the in-plane stress $\sigma_{hu}$ in the skins at which intra-cell buckling occurs as

$$\sigma_{hu} = \frac{2E_{fs}}{1-v_{fs}^2} \left( \frac{2t}{a} \right)^2, \quad (10)$$

where $a$ is the cell size (i.e. the diameter of the inscribed circle) of the honeycomb and $E_{fs}$ and $v_{fs}$ are the elastic modulus and Poisson’s ratio for the skin for loading in the axial direction. A similar expression, verified experimentally by Kuenzi [14], has been given by Norris [15]. Eqs. (9) and (10) can be used to derive the value of cell size above which there is transition from face yielding to intra-cell buckling as

$$a = 2t \sqrt{\frac{2}{1-v_{fs}^2}} \frac{E_{fs}}{\sigma_{fy}}. \quad (11)$$

2.1.3. Face wrinkling

Face wrinkling is a buckling mode of the skin with a wavelength greater than the cell width of the honeycomb (Fig. 3(c)). Buckling may occur either in towards the core or outwards, depending on the stiffness of the core in compression and the adhesive strength. In practice, with 3-point bending, inward wrinkling of the top skin occurs in the vicinity of the central load. By modelling the skin as a plate on an elastic foundation, Allen [1] gives the critical compressive stress $\sigma_{fs}$ that result in wrinkling of the top skin as

$$\sigma_{fs} = \frac{3}{(12(3-\nu_{ex})^2(1+\nu_{ex}))^{1/3}} E_{fs}^2 E_3^{2/3}, \quad (12)$$

where $\nu_{ex}$ is the out-of-plane Poisson’s ratio and $E_3$ the out-of-plane Young’s modulus of the honeycomb core (see Section 2.3).

2.2. Core failure

Honeycomb sandwich structures loaded in bending can fail due to core failure. Pertinent failure modes are shear failure or indentation by local crushing in the vicinity of the loads, as illustrated in Fig. 4.

2.2.1. Core shear

Assuming simple beam behaviour, the shear stress varies through the face and core in a parabolic way under 3-point bending. If the faces are much stiffer and thinner than the core, the shear stress can be taken as linear through the face and constant in the core. Neglecting the contribution from the skins, the mean shear stress in the core is given by

$$\tau_{ez} = \frac{W}{2d}. \quad (13)$$

Assuming brittle behaviour, failure occurs when the applied shear stress $\tau_{ez}$ equals the shear strength $\tau_{ez}$ of the honeycomb core in this direction.

$$\tau_{ez} = \tau_{ez}. \quad (14)$$

Low density Nomex cores are particular susceptible to this failure mode. Due to the anisotropy of the honey-

(a) Core shear  (b) Local indentation

Fig. 4. Failure modes in the core [13].
comb structure (Section 2.3) the shear strength of the core depends on the loading direction.

2.2.2. Local indentation
Failure of sandwich panels in 3-point bending can occur at the load point due to local indentation. Failure is due to core crushing under the indenter. The bending stiffness of the skin and the core stiffness determine the degree to which the load is spread out at the point of application. This mode of failure has not been adequately modeled for honeycomb sandwich panels. To include this important failure mechanism, we use a simple empirical approach used in handbooks on sandwich panel construction [13]. We assume that we know the length of contact $\delta$ between the central roller and the top skin. It is further assumed that the load is transferred uniformly to the core over this contact length, so that the out-of-plane compressive stress $\sigma_z$ in the core is given by

$$\sigma_z = W/\delta. \quad (15)$$

Failure is then predicted when this compressive stress equals the out-of-plane compressive strength $\sigma_{cc}$ of the honeycomb core.

$$\sigma_z = \sigma_{cc}. \quad (16)$$

The above approach is deficient in three respects (i) the contact area must be estimated in some way - in the experiments described in Section 4 this is measured, (ii) load transfer from the roller to the core is oversimplified; this will depend on the relative skin and core stiffnesses, (iii) failure in the core will not be governed solely by the compressive stress in the core but will also be influenced by the local shear stress. A more rigorous stress analysis of the contact region can be found in [16] and the authors are currently working on its implementation to predict local failure in honeycomb panels.

2.3. Honeycomb mechanics
To evaluate the failure mechanisms described in Section 2, stiffness and strength properties for the honeycomb core are required. Figure 5 illustrates the Nomex honeycomb structure. Nomex is constructed from ribbons of aramid paper running in the 2 direction (the ribbon direction). These are glued together at intervals along the ribbon and the stack of ribbons is then expanded into a honeycomb by pulling in the 1 direction. The paper substrate is finally dipped into phenolic resin to build up the walls of the honeycomb. Because of this construction method, the honeycomb is anisotropic; in particular walls normal to the 1 direction have two layers of paper, while other walls have only a single layer. In this section we use the results of Refs. [8,10] to express the properties of the honeycomb as a function of the properties of the solid material from which the honeycomb is made and the relative density $\rho_c/\rho_s$ of the honeycomb. Although the theory is applicable to any brittle honeycomb, in practice we will focus on the Nomex honeycomb core used in the beam failure experiments of Section 4. Expressions are compared with published experimental data to evaluate the applicability of the theoretical models to the Nomex honeycomb core and to find the most suitable expressions for use in the beam calculations.

2.3.1. Theoretical models of honeycomb mechanics
The honeycomb Poisson's ratio $\nu_{cc}$ required for the failure analysis (Section 2.1.3) is $\nu_{13}$ or $\nu_{23}$ for in-plane Poisson strains due to out-of-plane loading in the 3 direction. To a first approximation its value can be taken as that of the solid material (Eq. (4.64) in Ref. [8]), i.e. $\nu_{13} = \nu_{23} = \nu_s$.

The Young's modulus of the honeycomb in the out-of-plane 3 direction is given by the rule of mixtures expression

$$E_3 = \frac{\rho_c}{E_s} \frac{\rho_s}{\rho_c}. \quad (17)$$

In honeycombs, failure under out-of-plane compressive stresses occurs due to fracture of the cell walls or due to elastic or plastic buckling of the cell walls [9]. For Nomex honeycombs failure is due to a 'crushing' mechanism, initiated by elastic buckling and developing as a plastic buckling process. The relevant collapse strength $\sigma_{cc}$ can be simply estimated using the rule of mixtures expression, $\sigma_{cc} = \rho_c/\rho_s$, where $\sigma_{cc}$ is the compressive strength of the solid from which the core is made. Wierzbicki [17] gives an alternative expression for the failure stress based on a plastic collapse model. For a honeycomb with regular hexagonal cells this approach predicts the collapse strength

$$\sigma_{cc} = 3.25\sigma_{cc} \left( \frac{\rho_c}{\rho_s} \right)^{5/3}. \quad (18)$$

Zhang and Ashby [10] show that the out-of-plane shear strength and stiffness of honeycombs are independent of height and cell size. Honeycomb cores
exhibit slight anisotropy in their out-of-plane shear strength and stiffness, due to the set of doubled walls. By using simple mechanics models based on an array of regular hexagons and considering the double wall effect approximate expressions for the shear strengths $\tau_{31}$ and $\tau_{32}$ are derived as

$$\frac{\tau_{31}}{E_s} = 1.7 \left(\frac{\rho_c}{\rho_s}\right)^3,$$

(19a)

$$\frac{\tau_{32}}{E_s} = 2.6 \left(\frac{\rho_c}{\rho_s}\right)^3,$$

(19b)

and for the shear moduli $G_{31}$ and $G_{32}$ as

$$\frac{G_{31}}{G_s} = 0.375 \left(\frac{\rho_c}{\rho_s}\right),$$

(20a)

$$\frac{G_{32}}{G_s} = 0.6 \left(\frac{\rho_c}{\rho_s}\right).$$

(20b)

The core shear modulus $G_{c\infty}$ used in Eq. (6) to calculate the skin stress should be taken as either $G_{31}$ or $G_{32}$ depending on the orientation of the ribbon direction in the honeycomb. This anisotropy leads to a dependence of skin failure loads on the honeycomb orientation. Similarly the core shear strength $\tau_{c\infty}$ depends on the honeycomb orientation.

### 2.3.2. Experimental evaluation of honeycomb mechanics

The theoretical relations detailed in Section 2.3.1 are those that we use for our calculations in Section 3. In this section we compare the theoretical expressions with experimental data from reference [10] and manufacturers' data sheets [13] for honeycombs made of Nomex (aramid paper impregnated in phenolic resin). Often it is observed that there is a wide variation amongst data from different sources reflecting the wide manufacturing tolerances in the constituent aramid sheet (particularly $\rho_c$) and the difficulties in making accurate measurements.

The measurements of out-of-plane compressive properties are made by testing honeycombs under stabilised compression. As depicted in Fig. 6(a) the prediction of Eq. (17) for Young's modulus lies between the two sets of data and close to that of reference [10]. Figure 6(b) shows that Wierzbicki's [17] Eq. (18) for compressive strength fits the experimental data better than the usual mixture's law, reflecting the plastic collapse mechanism of Nomex under compression.

Figure 6(c) and (d) show plots of shear modulus and strength. Manufacturers' measurements are significantly higher than the measurements of Ashby and Zhang because of the different test setup. Ciba or Hexcel use a short beam test, where shear strength and stiffness are out-of-plane and measured indirectly (see Eq. (2) in Ref. [18]). Zhang and Ashby has tested the honeycombs in in-plane shear with an appropriate testing rig. We believe that the latter source gives a more direct estimate of shear properties. The major difference between Eqs. (19a) and (19b) and the experimental data of [10] for $\rho_c/\rho_s > 0.1$ are due to debonding of honeycomb specimens from the rig. We can use Eqs. (19a) and (19b) when $\rho_c/\rho_s > 0.1$, since in the material systems considered here no debonding occurs.

### 3. Construction of a failure mode map

Sections 2.1 and 2.2 have described various mechanisms of failure which occur with honeycomb sandwich panels, and the honeycombs mechanics needed to evaluate the failure loads for each of these mechanisms. In this section we describe how a map can be constructed detailing which failure mechanism actually occurs for a given material combination and beam geometry. This follows the work of Triantafillou and Ashby [7] for foam-core sandwich panels. The failure mode map is illustrated by way of example in Section 3.1. The failure loads depend on the properties of the skin and honeycomb solid material, the relative density $\rho_c/\rho_s$ of the core, the thicknesses $t$ and $c$ of the skin and the core, and the beam span $L$. Because we include indentation failure, failure also depends on the loading details. In the experiments we use rollers to apply the load, so that failure depends on the roller radius $R$. The failure line load $W_c$ can then be expressed as a function of the material properties and the beam parameters [7] $W_c = f(t/L, t/R, \rho_c/\rho_s)$. To evaluate this function the expressions for skin and core stresses (Eqs. (7), (13) and (15)) are substituted into the various failure criteria (Eqs. (9), (10), (12), (14) and (16)) as described in Section 2 to give the critical line loads as summarised in Table 1. The actual failure load and mode are given by the mode with the minimum failure load. Maps of the failure mode and failure load can then be drawn as a function of the beam geometry, for a given material system. The Matlab [19] programming language is used to evaluate the equations.

### 3.1. A failure mode map for beams with a GFRP skin and Nomex core

The above section describes how a failure mode map can be constructed for a honeycomb sandwich panel. This is illustrated in this section using sandwich panels made of GFRP laminate skins and Nomex honeycomb cores of different densities. The core and skin thicknesses $c$ and $t$ are 9.4 mm and 0.38 mm respectively and the nominal honeycomb cell size is 3 mm. Experimental results for this sandwich panel type are presented in

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3 Hexcel Composites formerly Ciba Composites.

4 Stabilised compression means restriction of the cell walls from slipping between the specimen and the rig plates during the test.
Section 4. Further details of the panel construction, materials and material properties are given in that section. Figure 7(b) shows the dependence of line load $W_f$ at failure on core relative density $\rho_c/\rho_s$ and face thickness to span $t/L$ ratio, for a value of the radius of the roller to the skin thickness $R/t$ of 26. Each surface corresponds to a different failure mode. The failure mode map, Fig. 7(a) is given by the projection of the intersections between failure surfaces on the $\rho_c/\rho_s - t/L$ plane. Slightly different failure maps are calculated depending on whether the honeycomb ribbon lies in the longitudinal direction along the beam axis, or transverse to the beam axis. Differences arise from the anisotropy in the strength and stiffness of honeycomb in shear (c.f. Eqs. (8), (19a) and (19b)). As noted in Section 2.2.2, failure by indentation is estimated using an empirical approach and relies on experimental measurements of the contact area as described in Section 4. Indentation is the only mechanism which depends on the roller diameter. This will be a more widespread mechanism of failure with smaller roll diameters. For the honeycomb geometry chosen for these plots, intra-cell dimpling is not predicted. At the map boundaries, the failure loads for the mechanisms either side of the boundary are equal. In practice failure near a boundary may be due to a combination of the two mechanisms and coupling between the two mechanisms may reduce the load below that predicted for each of the modes independently.

Fig. 6. Comparison of theoretical and measured out-of-plane (a) compressive modulus, (b) compressive strength, (c) shear modulus and (d) shear strength.
The failure mode map shown in Fig. 7(a) is useful where a designer has specified face and core thicknesses and wishes, for example, to select an appropriate span or relative density. More commonly, however, the span is fixed, a standard skin construction and thickness is specified, and only the core thickness or density can be relatively easily changed. In this case it is more useful to plot a map of the failure modes and loads as a function of core relative density and core thickness to span ratio $c/L$, at a fixed skin thickness to span ratio $t/L$ and roller radius to face thickness ratio $R/t$. Fig. 8 shows such maps for three typical values of $t/L$ with $R/t = 26$. Note that for long spans (Fig. 8(a)) the core crushing failure mode vanishes, while for short spans face wrinkling is not predicted (Fig. 8(c)).

4. Experiments

Sandwich panels were made of Nomex honeycomb core and GFRP laminate skins and were supplied by Hexcel Composites. All panels had the same skin cross-ply laminate on either side of the core, as depicted in Fig. 9. Each laminate comprises two glass prepregs: the outer with a resin content of 27% and the inner with 41%, giving a skin thickness $t$ of 0.38 mm. The Nomex honeycomb cores used in the panels are designated by the manufacturer as Aeroweb® type A1. Panels with core densities of 29, 48, 64 and 128 kg/m$^3$ were used. For most of the tests the honeycomb had a nominal cell size of 3 mm, but for tests described in Section 5.4 a cell size of 13 mm was used. The core thickness $c$ was 9.4 mm. Mechanical properties of the skin and the honeycomb’s constituent solid material (aramid paper + resin) are listed in Table 2. Since the compressive strength of the laminate has been inferred from compressive tests, this is not an independent measurement. Hexcel quote a value of 265 MPa, based on simple beam theory for long beams. With our beam model with a correction for shear in the core, a revised estimate for the compressive strength of the laminate of 300 MPa is inferred from the data at long spans.

Panels were cut into beams using a diamond wheel. A width $b$ of 40 mm was chosen so that it was greater than twice the sandwich height and three times the cell size, as recommended in by ASTM standards [20]. Beams were cut with the ribbon direction either in the longitudinal direction along the beam axis or in the transverse direction, as depicted in Fig. 9. Beams of varying spans and core relative densities were made to probe the various regions of the failure mode maps (Fig. 7). Specimens were tested in 3-point bending, applying the load through rollers of diameter of 20 mm (c.f. ASTM standard C393-62 [20]). The crosshead speed was kept constant throughout the test and was chosen so that the maximum load occurred between 3 and 6 min after the start of the test. Displacement of the central loading point relative to the end rollers was monitored using a LVDT and logged on a computer. The central section of the beam (where failure invariably occurred) was also recorded on a video recorder (Fig. 10) as the test progressed. To model failure due to local indentation (Section 2.2.2), it is necessary to define the value the length of the contact area $\delta$ between the central roller and the top skin. This was estimated experimentally by putting carbon paper between the roller and the specimen. For all the specimens tested $\delta$ was between 2 and 3 mm, with a typical value of 2.5 mm. This information was used to estimate the failure load due to indentation as described in Section 2.2.2.

4.1. Experimental results

Figure 11(a)-(d) show photographs of the section under the central load just after failure, illustrating four
failure modes observed during the tests of those beams with 3 mm honeycomb cell size. These were taken from videos recorded during the tests. Beam details for each of these figures are given in Table 3; to scale the photographs note that the cell size is 3 mm for all the specimens of Fig. 11, except Fig. 13(a) and (b) which has the larger cell width of 13 mm. For clarity the roller seen in the top half of the figures has been outlined in some cases. Corresponding load–deflection curves are included in Fig. 11. With all the failure mechanisms except intracell buckling (Fig. 13(a) and (b)) and core shear (Fig. 11(d)), failure occurred in a brittle manner.
with little non-linearity in the load displacement curves before failure and a sharp drop in load at failure. For short span tests where indentation occurred (Fig. 11(c)), the beam has a significant post-failure strength as the core progressively crushes. Table 3 presents the average line loads $W$ at failure and corresponding observed failure mechanisms. The mode is described as ‘Complex’ when failure appeared to occur simultaneously in the core and in the face. Those mechanisms denoted as ‘mode 1 $\to$ mode 2’ (i.e. Intracell dimpling $\to$ core crushing) indicates the appearance of mode 1, as elastic instability before the final failure mode 2.

The measured effect of skin thickness to span ratio on the failure load is compared with theory in Fig. 12(a)–(d) for the different core densities. The theoretical graphs are sections through the load surface, Fig. 7(b), at constant core relative density. Experimental mechanisms of failure are indicated on these graphs to allow a comparison between the actual and predicted failure mechanisms.

5. Discussion

Figure 12 shows that, in general, the experimental failure loads agree satisfactorily with theoretical values and that the observed failure modes are generally the same as the predicted modes (Fig. 7). Where a transition from one failure mode to another occurs, the mechanism of failure is mixed, but the failure load is still adequately predicted. The main source of deviations arises from the
errors in predicting the honeycomb material properties (Section 2.3).

5.1. Skin failure

The laminate face yielding strength has been chosen to fit data at long spans, as discussed in Section 4. At the longest spans with the 64 kg/m³ honeycomb, face yield occurs although wrinkling is predicted, but as shown in Fig. 7(a), these points are very close to the boundary between these two mechanisms.

5.2. Core failure

Failure load predictions for core crushing are adequate for the higher density cores but predictions are poor for the lower density cores. The photograph in Fig. 11(d) illustrates a beam with a low density core in the transverse direction near the failure load, where core shear failure is predicted. Final failure is a mixture of core shear and crushing under the indenter. The difference in the initial slopes of the load-deflection curves for the specimens with different ribbon directions reflects the anisotropy associated with the core shear stiffness (Eq. (8)). Non-linearity in the curve for the transverse direction indicates that there may be some ductile shear of the core prior to final failure. The significant under-prediction of the failure load (Fig. 12(d)) due to core shear is because final failure does not occur when the core fails in shear. Predictions of failure based on the core crushing strength would give a relatively good agreement with measurements in this case. Again this highlights the need for more elaborate models of core failure near loading points.

5.3. Effect of ribbon direction

Specimens with ribbon running in the longitudinal direction fail at a significantly higher load than those with ribbon in the transverse direction in all cases except where failure is by intracell dimpling (Section 5.4). For face failure modes, a slight difference is predicted, associated with the effect of core shear stiffness on the stress in the skins, although the measured differences are somewhat greater than the prediction. The theoretical model described for core crushing does not include any anisotropic material properties. The substantial difference between the strengths for the two ribbon orientations suggest that an improved model is necessary, looking in more detail at the stresses around an indenter and including the effect of core shear.

5.4. Intra-cell buckling

Section 2.1.2 defines a critical honeycomb cell size above which failure occurs by intra-cell buckling instead of by top face yielding. For the materials used here, this transition is predicted at a cell size of approximately 9mm. This hypothesis was tested by using specimens with a cell size 13 mm, a core density of 64 kg/m³ and a range of skin thickness to span ratios. All of the specimens with the larger cell size exhibited elastic intracell buckling. Final failure did not occur immediately, but at a higher load, either by delamination of the top-face or by core crushing for long or short spans respectively. Fig. 13(a) shows the section under the central roller at the onset of intra-cell buckling, while Fig. 13(b) shows the section when final failure occurs by delamination. Fig. 13(c) compares the failure load and failure mechanisms for this set of tests. The theory (Eq. (10)) under-predicts the final failure load because it relates to the initial buckling instability and not the final delamination or core failure. Failure loads are independent of the honeycomb ribbon direction, because the single and double-walls paper walls make up a smaller proportion of the honeycomb for a given honeycomb density.

6. Conclusions

Previous research on honeycomb mechanics and the behaviour of sandwich beams in 3-point bending have been combined to model the behaviour of honeycomb sandwich panels. It is assumed that the skin and core materials behave in a brittle manner. The failure mechanisms considered were face yield, face wrinkling, intra-cell buckling, core shear and indentation at the
load points, leading to core crushing. The latter is treated in an empirical way, using measurements of the bearing area at the load points. The failure loads for each region are estimated assuming that there is no coupling between failure mechanisms. Following the work of Triantafillou and Gibson [7], failure mode maps

(a) Face yield ($\rho_c/\rho_s = 128 \text{ kg/m}^3$, $L = 340 \text{ mm}$)

(b) Face wrinkling ($\rho_c/\rho_s = 48 \text{ kg/m}^3$, $L = 380 \text{ mm}$)

(c) Core crushing ($\rho_c/\rho_s = 128 \text{ kg/m}^3$, $L = 60 \text{ mm}$)

(d) Core crushing ($\rho_c/\rho_s = 128 \text{ kg/m}^3$, $L = 340 \text{ mm}$)

Fig. 11. Photographs of the different failure modes (for 'T' ribbon direction) and corresponding load deflection curves (for both 'L' and 'T' ribbon directions).
Table 3
Experimental results

<table>
<thead>
<tr>
<th>Core density (kg/m³)</th>
<th>Honeycomb ribbon direction</th>
<th>Span length (mm)</th>
<th>t/L</th>
<th>Measured line fail.load (kN/m)</th>
<th>Observed failure modes</th>
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</table>

Photographs of failure given in Figs. 11 and 13 correspond to the entries in italics in the final column of this table.

are derived with axes as the core relative density and the ratio of the face thickness to span length. Each map is appropriate for a single value of the ratio of the radius of the roller to the skin thickness. Regions in which the various failure mechanisms occur are identified on the maps. Alternative axes for the map of relative density and the ratio of skin to core thickness are suggested, as a more useful set of parameters for a beam designer or
manufacturer. Although the maps are generated for 3-point bending, the method can straightforwardly be applied to other loading geometries, for example 4-point bending. The method is illustrated using the widely used combination of cross-ply GFRP laminate skins with a Nomex/phenolic resin honeycomb core.

Experimental tests showed that, in general, the maps predicted adequately failure modes and failure loads. The transition from face yielding to intra-cell buckling for long span beams was demonstrated by increasing the honeycomb cell size from 3 to 13 mm. Failure near the load points due either to core shear or core indentation was not modelled well. To model this behaviour more sophisticated models of the contact region and of the failure criteria in the core are needed. The authors are currently working on implementation of the higher order beam theory of Frostig [16] to produce an improved indentation failure analysis for honeycomb panels.

Acknowledgements

The authors are most grateful to Hexcel Composites for their help in supplying materials and for the technical assistance of Mr. Nigel Hookham and Mr. Peter Clayton. Thanks are due to Messrs. Alan Heaver and Simon Marshall for their valuable contribution to the experiments and to Prof. Norman Fleck for his advice. The authors acknowledge with gratitude the financial support of the Greek Government and the US Office of Naval Research (grant number 0014-91-J-1916).
Core Density = 64 kg/m³
Cell size = 13 mm
Span Length = 230 mm

(a) Elastic intra-cell buckling  (b) Final failure due to top skin delamination

(c) Experimental results compared with theory

Fig. 13. Photographs and results of specimens with 13 mm cell size.
References