Thermal Expansion of Honeycomb Sandwich Panels

H. CHEN, D. W. OAKES and E. G. WOLFF

ABSTRACT

Hygrothermally induced dimensional changes can be predicted for many composite materials and structures, such as CFRP laminates. When laminates are combined with honeycombs or foams, the core structure and adhesive layers modify a laminate based prediction for thermal expansion coefficients. A theory accounting for anisotropic core properties to predict coefficients of thermal expansion is described and compared with measurements.

INTRODUCTION

Sandwich panels combine the high stiffness, strength and dimensional stability of laminates such as carbon fiber reinforced plastic (CFRP) composites with the flexural stiffness and lightweight afforded by a honeycomb (H/C) or foam core. Their hygrothermal behavior is of special interest to the integrity of solar panels [1], antenna structures [2,3], aircraft [4,5] and payload fairings.

Computational approaches to the prediction of coefficients of thermal (CTE) and moisture (CME) expansion of sandwich panels were considered in [6-9]. Through-thickness thermal or moisture gradients were calculated based on facesheet properties and core thickness [6]. Laminate theory simulation where honeycomb was assumed to be plies with equivalent properties was compared with 3D finite element modelling [7]. Discrepancies were found in Poisson ratios and thermal expansion coefficients, mainly due to the effect of free edges in the relatively small sizes used for the finite element modelling. Theoretical calculations of the thermal expansion of CFRP/aluminum/CFRP composite spherical shells over the range 90-380K led to radial strain predictions, dominated by the properties of the CFRP skins [8]. A thin shell finite element study [9] of the effect of adhesive on the CTE of sandwich panels was compared to measurements made by electro-optical displacement detectors. Agreement ranged from -0.66 ppm/K measured and -0.62 ppm/K predicted to -0.25 ppm/K measured with -0.40

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ppm/K predicted. Hygrothermal effects on buckling behavior of laminated plates [10] include criteria for phenomena caused by curing and thermal cycling induced stresses, such as shear crimping, face wrinkling [11], face dimpling [3], monocell and/or intercellular buckling, and delamination. Thermal buckling and transverse shear deformations in face sheets with moderately thick cores are considered in [12].

Analytical approaches for developing zero CTE satellite structures were developed by groups at Nippon Oil and the National Aerospace Laboratory [13], and Mitsubishi and Nihon University [2, 14]. Adjustment of the relative thickness of high modulus (negative CTE) CFRP facesheets with Al H/C cores can result in a zero CTE sandwich construction [13]. The original predictive model [14] did not utilize the effect of the adhesive layer, and measured values for CTE were higher than predicted. Agreement with experiment [13] ranged from 0.45 (ppm/K) measured and predicted to -0.10 (ppm/K) (measured) with 0.14 (ppm/K) (predicted). Work on Kevlar fabric with cyanate resin facesheets with a Kevlar fiber reinforced plastic (KFRP) honeycomb core gave comparable agreement between measurements and a laminate theory based predictive model [2]. This paper illustrates its general use for CTE with CFRP/Al H/C/CFRP structures. (We have also adopted this theory to predict CMEs [15]).

THEORY

Table I gives symbols. General laminate theory defines the linear in-plane expansion coefficient for layered structures;

$$\alpha_x = \frac{A_{yy}N_x - A_{xy}N_y}{A_{xx}A_{yy} - A_{xy}^2} = (\varepsilon_x + z\,\kappa_x) / \Delta T \tag{1}$$

$$\alpha_y = \frac{A_{xx}N_y - A_{xy}N_x}{A_{xx}A_{yy} - A_{xy}^2} = (\varepsilon_y + z\,\kappa_y) / \Delta T \tag{2}$$

where x, y and z are the principal laminate directions, ε and κ are the strain and curvature, A is the inplane sandwich stiffness, and N the thermally induced load. We combine the facesheet, adhesive and core layers to write for the x-direction;

$$A_{xx}\,(\text{sand}) = A_{xx}\,(\text{f/s} + \text{adh}) + (\,Q_{xx} * \text{h})\ \text{core} \tag{3}$$

$$\begin{aligned} N_{xx} = \Delta T\ \{&(A_{xx} * \alpha_x + A_{xy} * \alpha_{xy})\ \text{f/s+ adhesive} \\ &+ (Q_{xx} * \alpha_x + Q_{xy} * \alpha_y) * \text{h core})\} \end{aligned} \tag{4}$$

TABLE I. PARAMETERS FOR SANDWICH CTE PREDICTION

PARAMETERS	SAMPLE CALCULATION	UNITS
Fiber	M50J	-
Fiber modulus E_f	500	GPa
Resin	954-2A	-
0-deg ply modulus E_1	321	GPa
90-deg ply modulus E_2	10	GPa
Poisson's ratio ν	0.25	-
Ply shear modulus G_{12}	8	GPa
0-deg ply CTE α_1	-0.85	ppm/deg C
90-deg ply CTE α_2	23	ppm/deg C
Ply thickness h_p	1.59e-4	m
Ply layup	[0/45/90/-45] s	-
Adhesive thickness h_a	2.54e-5	m
Adhesive modulus E_a	3.45	GPa
Core foil thickness t	2.54e-5	m
Core material modulus E_c	69	GPa
Core cell side a	3.22	mm
Core cell length l	7.58	mm
Core cell diameter d	6.30	mm
Core expansion angle θ	53.7	degrees
Core thickness h_c	0.0508	m
Core material CTE	23	ppm/deg C

The first term in Eq. 3 is obtained with standard laminate theory. Expressions for the reduced stiffnesses Q_{ii} of the core material are taken from the model of Inoue [14] who assumed that the cell walls react only in-plane. The tension/compression corner and flexural variations of the honeycomb core were considered. The reduced stiffnesses for the core are:

$$Q_{XX} = E_c / [\gamma H_1(\theta)H_3(\theta)] \tag{5}$$

$$Q_{YY} = E_c / [\gamma H_2(\theta)H_3(\theta)] \tag{6}$$

$$Q_{XY} = Q_{YX} = [E_cH_4(\theta)] / [\gamma H_1(\theta)H_2(\theta)H_3(\theta)] \tag{7}$$

$$H_1(\theta) = \sin^3\theta / (1 + \cos\theta) \tag{8}$$

$$H_2(\theta) = (1 + \cos\theta) * \cos^2\theta / \sin\theta \tag{9}$$

$$H_3(\theta) = 2 + (1+\cos^2\theta)/\sin^2\theta + \sin^2\theta/\cos^2\theta \tag{10}$$

$$H_4(\theta) = \sin\theta * \cos\theta \tag{11}$$

$$\gamma = a/t \tag{12}$$

$$\theta = \tan^{-1} d / (1 - a) \tag{13}$$

Figure 1 shows the relationships between the cell dimensions a, d and l. θ is the core expansion angle. Figure 2 shows that the Q_{ii} vary significantly with expansion angle. The numbers apply to an aluminum core with $t = 2.54e^{-5}$ m and a = 3.18 mm. These curves are directly proportional to foil thickness or the (isotropic) core material modulus and inversely proportional to the hexagon side length.

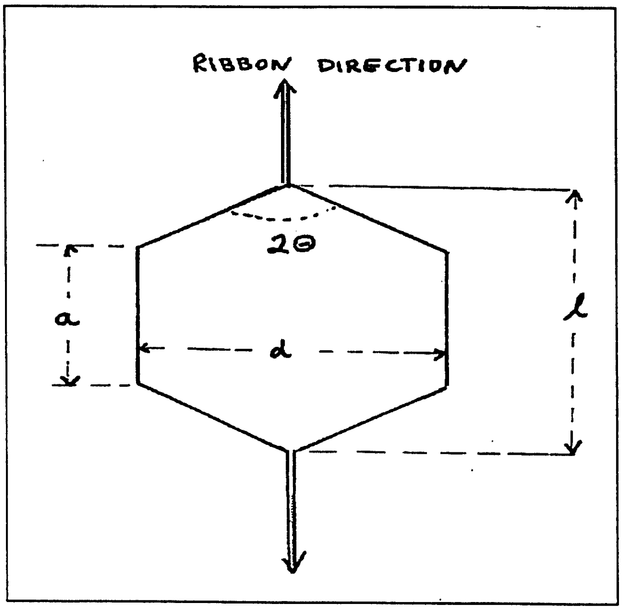

Figure 1. Relations Between Hexagonal Cell Dimensions

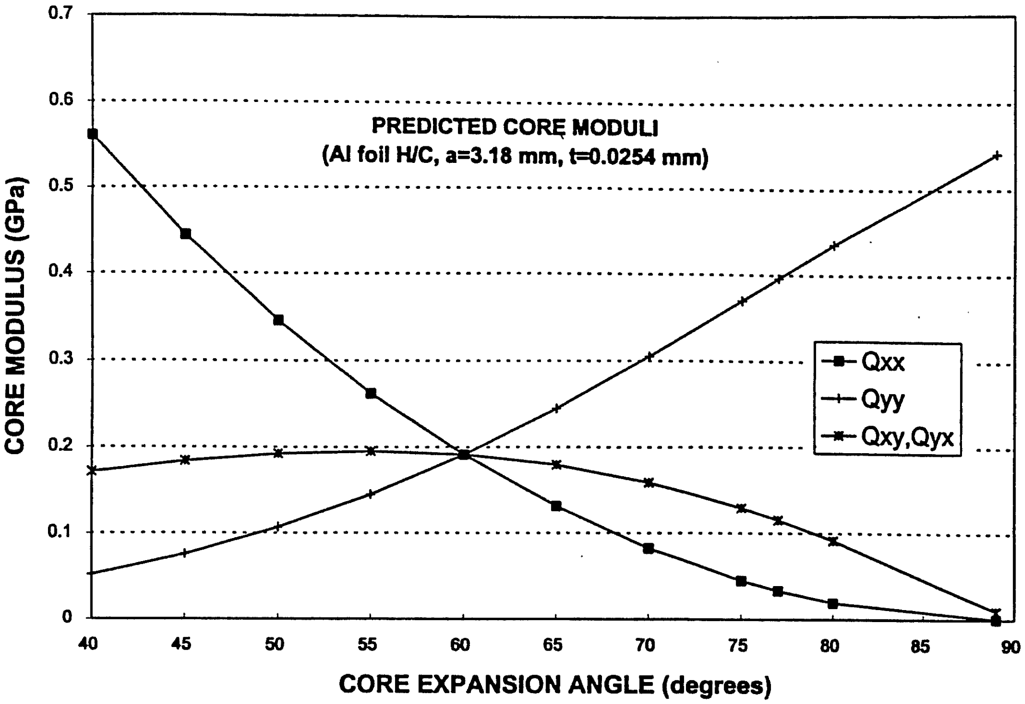

Figure 2. Variation of Core Moduli with Angle of (Hexagonal) Core Expansion

CTE MEASUREMENT TECHNIQUES

Michelson interferometry with reflecting mirrors is the preferred measurement technique because a) unlike strain gages, there is no test system variability or environmental sensitivity, b) resolution of better than +/- 0.01 ppm is needed not only to measure near zero in-plane CTE but to monitor changes with thermal cycling, c) large panels (e.g. >0.05 m^2) are required when cell dimensions are large (e.g. >5 mm diameter), and d) unlike strain gauges, interferometry does not affect the measurement by producing a stress field around the sensor. Measurements are made away from the edges to avoid the altered stress state caused by cell dimensions (typically on the order of size of the cell length). Placement of reflecting surfaces, through-thickness measurements, effects of face sheet dimpling and mid-plane asymmetry are discussed in [16,17]. Inflexions in the cooling/heating curves may be due to toughening additives to resins, adhesives such as ethyl vinyl acetate which cause low temperature phase transitions and/or separate phases which have low glass transition temperatures. The T_g of RTV silicone adhesives typically used to attach solar cells also shows inflections in thermal strain-temperature curves at low temperatures.

CTE TEST RESULTS

In-plane CTE values of CFRP quasi-isotropic laminates range from -1 to +1 ppm/°C as the fiber modulus decreases. The core raises these values especially as the core to facesheet thickness ratio increases. The core cell expansion angle is typically 45-55 degrees. This results in sandwich anisotropy, with the ribbon direction CTE more positive than the cross ribbon direction. The above theory predicts these values to within 20% with the deviations explained by the uncertainties in the parameters listed in Table I.

For the example in Table I, the isostrain parallel connected model for 0-deg unidirectional stiffnesses ($E_1 = E_f V_f + E_m V_m$) predicts E_1 = 321 GPa, assuming V_f = 0.65 and E_m = 7GPa. The CTE of a unidirectional ply is given by the Turner equation: $\alpha_1 = (\alpha_f V_f E_f + \alpha_m V_m E_m) / (E_f V_f + V_m E_m)$ as α_1= -0.85ppm/°C (assuming α_f = -1.04ppm/°C [18]). Laminate theory predicts $\alpha_x = \alpha_y$ = 0.037ppm/°C for the quasi-isotropic facesheet. This agrees with the measured α_x = 0.13 ± 0.15ppm/°C and α_y = 0.07±0.12 ppm/°C (for 10 samples). Equations 5-12 calculate the Q_{ii} to be used in Eqs. 1-4. Laminate theory gives the A_{ii} for the combined facesheets and adhesive (Eq. 3). The sandwich CTEs were predicted to be α_x = 1.45ppm/°C and α_y = 0.738ppm/°C which compares favorably to the measured values of α_x = 1.55 +/- 0.08ppm/°C and α_y = 0.713 +/- 0.04ppm/°C (6 samples, 3 cycles each). Figure 3 shows typical results from these measurements in terms of thermal strain versus temperature. The results given here are typical inasmuch as the relative values of α_x and α_y, are correctly predicted. The sandwich $\alpha_x > \alpha_y$ as expected from Fig. 2, since $Q_{xx} > Q_{yy}$ for $\theta < 60$°C.

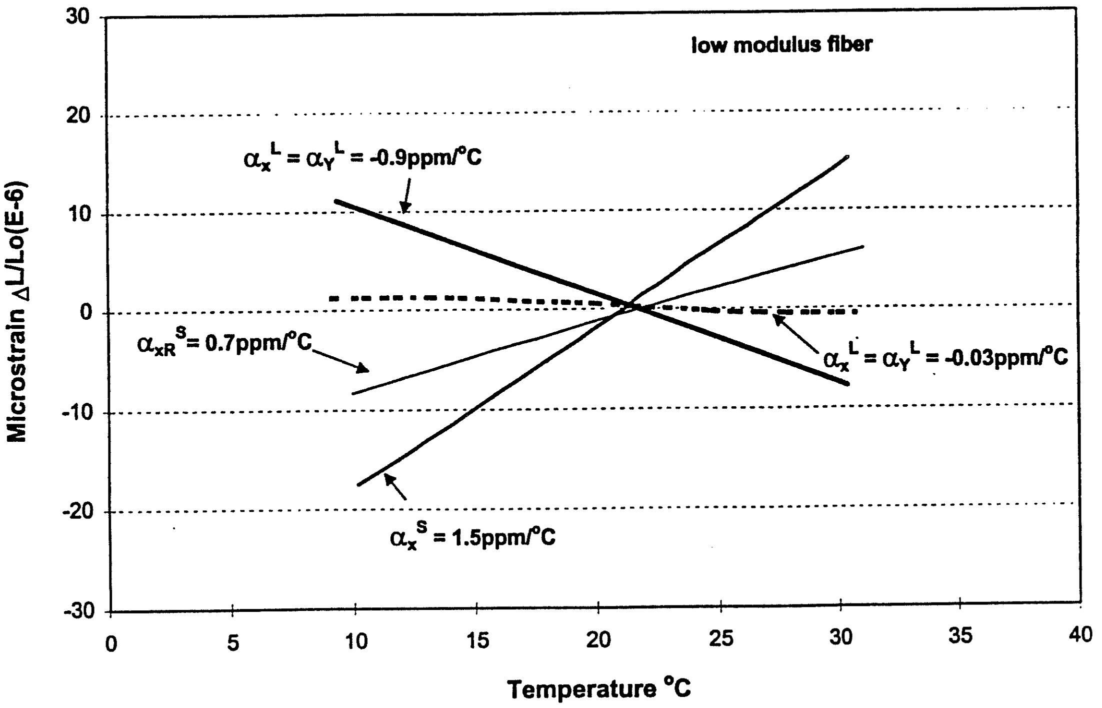

Figure 3. Typical In-plane Thermal Expansion of CFRP Facesheets and Sandwich with Aluminum Honeycomb Core

DISCUSSION

Deviations between theory and measurement may occur by a number of factors such as localized delamination or disbonds between the facesheets and core. This could explain occasions where the predicted α_x or α_y exceeds the measured values. The adhesive thickness is an uncertainty as its layer thickness is diminished by bonding pressure. Adhesive variables include node bonding, fillets, scrim cloth, wicking, core splice foaming adhesives and potting compounds/core fillers. Core variables include honeycomb type e.g., (hex, reinforced hexagon, flex-core, rectangular, etc.), ribbon orientation relative to facesheet, and venting through pinholes. Sandwich variables include residual stresses, print-through and shear crimping. The anisotropy of the core (e.g., ribbon direction) can also effect the rate at which microcracking and CTE stabilize [19].

CONCLUSIONS

The laminate plate theory and the honeycomb core stiffness theory of Inoue et al. [14] can be used to predict the inplane CTE of sandwich panels. A cell expansion angle deviating from 60°C leads to an anisotropic sandwich, even with quasi-isotropic facesheets. The effects of the structural parameters on CTE can be verified by laser interferometry measurement techniques.

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