HYGROTHERMAL DEFORMATION OF COMPOSITE SANDWICH PANELS

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SUMMARY: Coefficients of thermal and moisture expansion (CTE and CME) can be predicted for many composite laminates and sandwich panels. Core and adhesive properties, such as geometry, material moduli and expansion coefficients are important variables. Laminate theory is augmented with a modified model for anisotropic core properties to predict the CTE and CME of sandwich panels. Procedures to measure both CTE and CME are described. Since these are thermodynamic properties, methods to obtain equilibrium moisture strains are needed. Results are given for CFRP facesheets with Al and NOMEX honeycomb cores, and for woven Kevlar facesheets with Al cores. Tests with both sealed and unsealed edges are analyzed. Diffusion in unsealed sandwich panels, especially with moisture absorbing facesheets and/or cores is non-Fickian and requires a three dimensional analysis to obtain equilibrium data.

KEY WORDS: Moisture, hygrothermal, expansion, sandwich, dimensional stability, panels, laminates, absorption,

INTRODUCTION

Sandwich panels typically consist of midplane symmetric composite facesheets, adhesive layers and honeycomb or foam cores. Their hygrothermal stability affects the integrity of solar panels, antenna structures, optical benches, radomes, windmill blades and many commercial aircraft, marine and transportation structures. Core materials include aluminum, NOMEX (aromatic polyimide), KOREX (aramid/phenolic, TYVEK (high density polyethylene), KRAFT paper (softwood), KEVLAR (aramid) honeycombs, plastic foams, fiberglass and developmental materials such as bias or straight graphite fabrics with phenolic or polyimide resin. Moisture produces complex changes in sandwich integrity, for example, it can retard cure and produce porous skin to core adhesive bonds [1]. As a result, hygrothermally induced distortions of sandwich panels are difficult to predict and measure.

BACKGROUND

Facesheet behavior alone can be analyzed in terms of classical laminate theory coupled with Fourier’s law of heat flow or Fickian diffusion for moisture equilibrium [2,3]. Prediction of inplane strains and curvatures of honeycomb panels as a result of through-thickness thermal or moisture gradients was outlined in [4]. (This work was based only on facesheet properties and core thickness). Computational approaches to the prediction of coefficients of thermal

(CTE) and moisture (CME) expansion of sandwich panels were compared [5]. Discrepancies were found in Poisson ratios and thermal expansion coefficients, mainly due to the effect of free edges in the relatively small size used for the finite element modeling. Limited work has been reported on the hygral stability of sandwich panels [2,6-13]. Analytical approaches for developing zero CTE satellite structures [6-8] found that the CTE is highly dependent on the model used for the equivalent stiffness of the core material. The effect of adhesive on the CTE was modeled by finite element analysis [9]. Moisture ingression into honeycomb panels depends on material, core density and direction [12]. Sandwich structures generally have lower CME values than their facesheets alone. Both strain and moisture content continue to change after the Fickian diffusion model predicts equilibrium has been reached [13].

THEORY

Laminate theory based on ply data (α_i ,β_i , i = 1,2) and directional core stiffness values can be used to predict sandwich CTE and CME values. The linear in-plane hygrothermal expansion coefficients for layered structures are defined as:

$$\alpha_i\,,\ \beta_i = \frac{A_{jj}\ N_i - A_{ij}\ N_j}{A_{ii}\ A_{jj} - A_{ij}^2} = \varepsilon_i\ /\ \Delta T,\quad \Delta M \tag{1}$$

where i,j = x,y, the laminate principal directions. A_{ij} are the inplane sandwich stiffnesses, N_i are the hygrothermally induced loads and ε_i are the inplane strains. We combine the facesheet and adhesive layers to write, for example, for the x-direction;

$$A_{xx} = \Sigma\ (Q_{xx}\ h_i)_{\text{f/s + adhesive}} + (Q_{xx}\ h)_{\text{core}} \tag{2}$$

$$N_{xx} = \Delta T\ \{\ (A_{xx}\ \alpha_x + A_{xy}\ \alpha_{xy})_{\text{f/s + adhesive}} + (Q_{xx}\ \alpha_x + Q_{xy}\ \alpha_y) * h_{\text{core}}\ \} \tag{3}$$

$$= \Delta M\ \{\ (A_{xx}\ \beta_x + A_{xy}\ \beta_{xy})_{\text{f/s + adhesive}} + (Q_{xx}\ \beta_x + Q_{xy}\ \beta_y) * h_{\text{core}}\ \} \tag{4}$$

The first term in Eq. 2 for facesheets and adhesives can be obtained with standard laminate codes. The core has a significant stiffness effect which alters the hygrothermal expansion of the sandwich from that of the facesheets alone. We have recently extended the model of Inoue [7] for CTE of sandwich panels to CME [3]. Figures 1 and 2 show the model of a honeycomb sandwich panel used for analysis. Here the stiffnesses Q_{ij} are functions of cell hexagon side length (a), core foil thickness (t), material stiffness (E_c), and angle of core expansion (θ) relative to the ribbon direction. In summary;

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

$$Q_{yy} = E_c \,/\, (\gamma H_2(\theta) H_3(\theta)) \quad (6)$$

$$Q_{xy} = Q_{yx} \;[E_c H_4(\theta)] / [\gamma H_1(\theta) H_2(\theta) H_3(\theta)] \quad (7)$$

$$H_1(\theta) = \sin^3\theta \,/\, (1 + \cos\theta) \quad (8)$$

$$H_2(\theta) = (1 + \cos\theta)\cos^2\theta \,/\, \sin\theta \quad (9)$$

$$H_3(\theta) = 2 + (1 + \cos^2\theta)/\sin^2\theta + \sin^2\theta/\cos^2\theta \quad (10)$$

$$H_4(\theta) = \sin\theta\cos\theta \quad (11)$$

$$\gamma = a / t \quad (12)$$

Note that $\theta = \tan^{-1} d / (l\text{-}a)$. Fig. 3 shows that the effective moduli vary significantly with expansion angle. Using a typical CFRP 8-ply facesheet with a quasi layup [0/45/90/-45]s, with E_1= 351 GPa, E_2 = 8.9 GPa, and G_{12} = 7.6 GPa, ν_{12} = 0.3, and a 9.9 mm thick Al H/C core, we see in Fig. 4 the effect of core on the CME of the sandwich compared to the facesheets with a layer of adhesive on each. A thicker core increases the spread of CMEs at any expansion angle (except at 60 degrees).

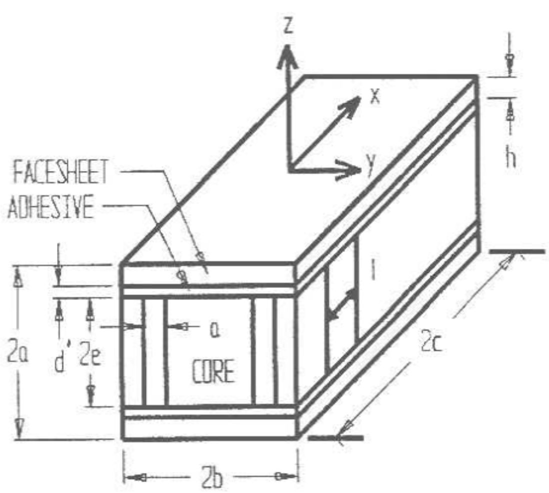

Fig. 1: Schematic of Sandwich panel.
d^1 = adhesive thickness
d = cell width

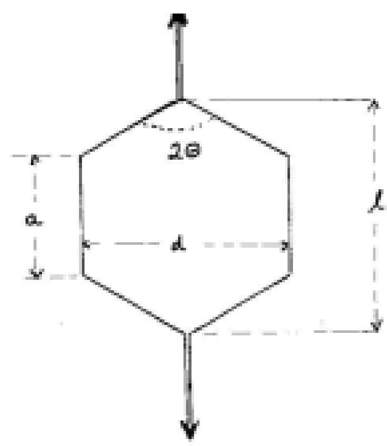

Fig.2: Ribbon parameters
Ribbon is vertical.

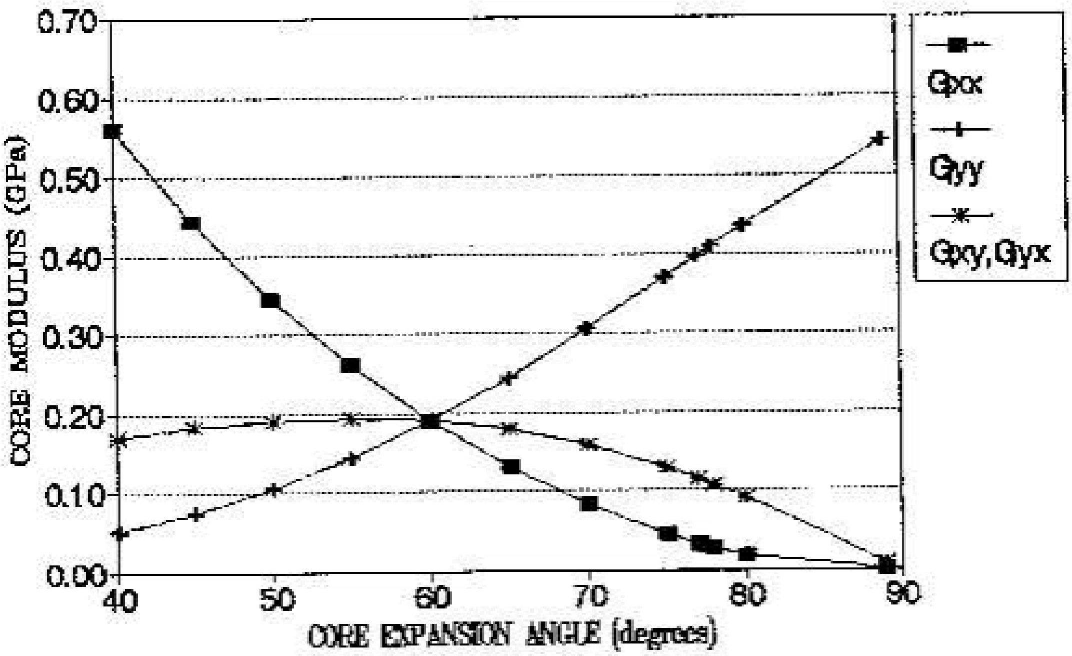

Fig. 3: Predicted Core Moduli as a Function of Core Expansion Angle.
Al honeycomb, quasi CFRP facesheets, $\gamma = 125$.

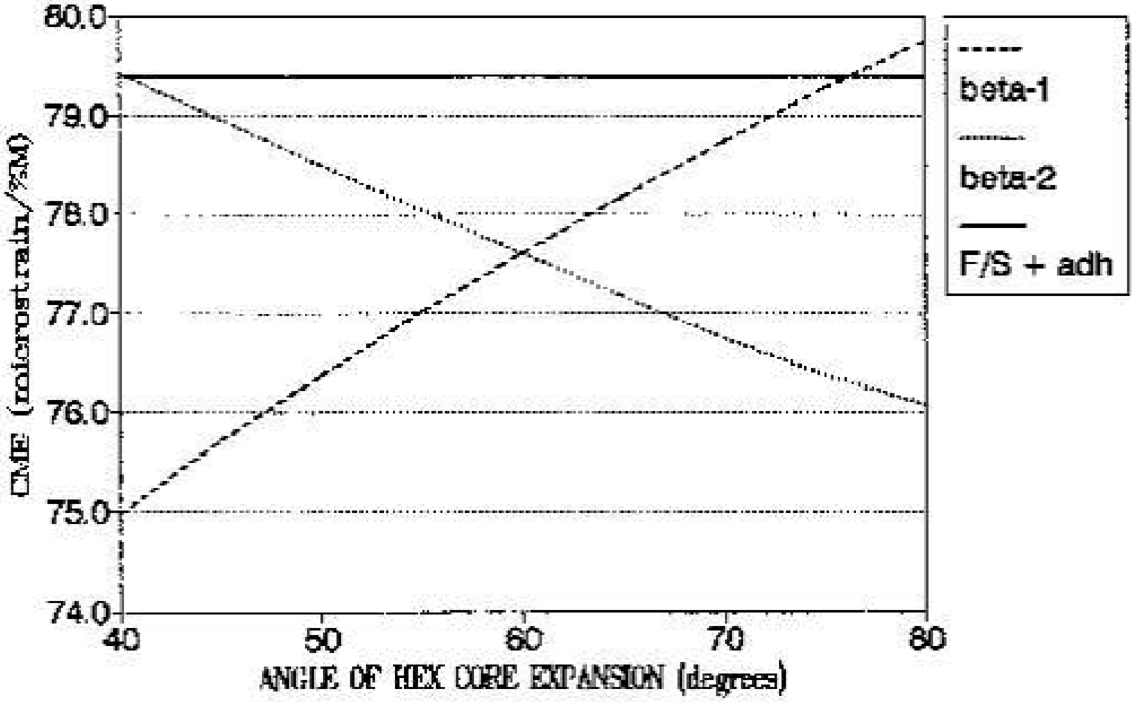

Fig. 4: Predicted CME of CFRP facesheets with adhesive and 9.9 mm Al Honeycomb
$\gamma = 110$. Compare measured values from Table I.

EXPERIMENTAL

CTE: Thermally induced X, Y, and Z dimensional changes be measured by Michelson interferometry [14,15] for a variety of sample dimensions and temperatures from at least 4-1000K. An important test factor is elimination of edge/end effects as the core cell size affects deformations near the edges. While temperature (unlike moisture) equilibration is normally rapid a common problem is midplane asymmetry. Control of ply and adhesive thicknesses, print-through of core features on thin facesheets (dimpling) and off-axis ribbon directions are often due to manufacturing problems. Methods to handle resultant distortions were outlined in [14]. Data for CTE of sandwich structures are given in [6,8,9,15].

CME - FACESHEETS Eq. 1 requires determining a uniform strain corresponding to a uniform moisture content change. This is accomplished in four steps;

1) Complete dryout, preferably in a vacuum at $T < T_g$ [16].
2) Edge sealing [17]
3) Maintenance at 1 atm air with a given relative humidity with salt solutions [18] and periodic weighing (at 24^oC) until moisture saturation.
4) Continuous strain measurement with LVDTs in dry air at the same temperature. Stable connections to LVDTs avoiding end effects are critical.

Steps 3 and 4 have been carried out at elevated temperatures, but more reliable data are obtained at a constant room temperature. This is because of cooling effects during weighing and temperature dependence of LVDT output. During an initial absorption interval the diffusivity D_z. is derived from the slope of ΔM vs. $\sqrt{t}$ [19];

$$D_z = \pi \, (h / 4 \, M_m)^2 \, [\, (M_2 - M_1) \, / \, (\sqrt{t_2} - \sqrt{t_1}) \,]^2 \qquad (13)$$

where h is the sample thickness, $M = \Delta W/W_o$ and M_m is the equilibrium mass change. For thin laminates with sealed edges and more than six plies, one can assume that the inplane strain is proportional to the fractional weight change G [20].

$$\varepsilon_x (t) = G * \varepsilon_{x\,(t = \infty)}, \qquad \varepsilon_y (t) = G * \varepsilon_{y\,(t = \infty)} \qquad (14)$$

$$G = (M(t) - M_o) / (M_m - M_o) = 1 - \exp [-7.3 \, (D_z * t / s^2)^{0.75}] \qquad (15)$$

where s = h for moisture access to both laminate sides, and s=2h if one side is restricted [19]. The strain data $\varepsilon_x (t)$ are plotted against the parameter G, and the curve is extrapolated (via a linear regression fit) to G = 1 (equivalent to t = oo). The CME is then obtained from Eq.1. Figure 5 illustrates a typical plot of strain versus the G parameter.

CME – SANDWICH: The importance of sandwich edges during changes in hygrothermal conditions has been stressed [21]. Consequently, sandwich panels were initially tested with edge seals. Some typical results are presented as follows.

RESULTS WITH EDGE SEALED PANELS

Graphite with Al Honeycomb Core: Typical (edge-sealed) moisture absorption data are shown in Fig. 6. In some samples, equilibrium has been reached and extrapolation methods are unnecessary. The two types of samples have the Al core ribbon direction along the sample measurement axis (L) and across it (W). Subsequent desorption strains are different for the two samples, and this is explainable by considering the core cell expansion angle. The results are compared to predictions in Table I and agree also with the trend in Fig.4. Data for the facesheets alone were unavailable. However, measured CME values for quasi-isotropic laminates of M50J/954-2A indicated $\beta x = \beta y$ = 103e-6/%M. This implied a β_1 = 20e-6/%M and β_2 = 2500e-6/%M. With the stiffer M55J fiber laminates and a resin which absorbs less moisture, these ply values were reduced about 80% which then gave the predictions of 75 and 79 ppm/%M.

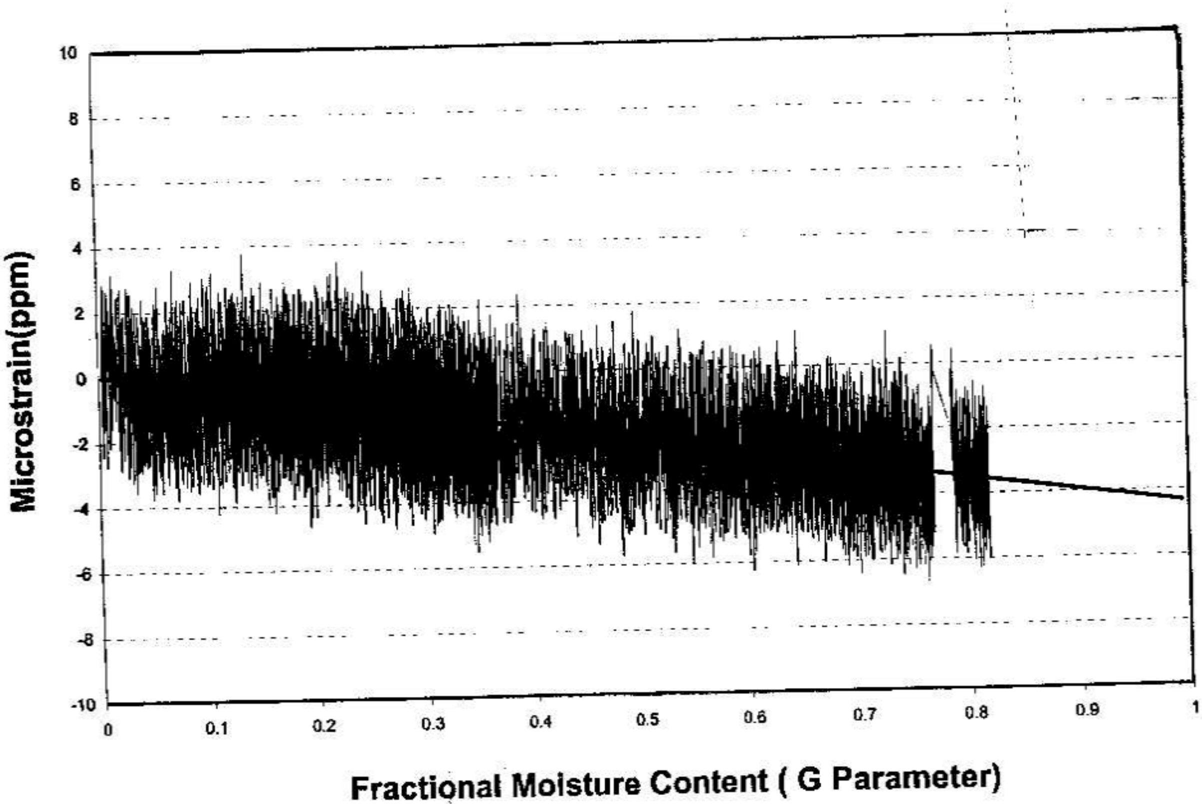

Fig. 5 : Moisture Induced Desorption Strain from Saturation at 53%RH to 0% RH at 24^0C for a Unidirectional Hybrid Carbon Based Laminate.

Graphite with NOMEX Core: Nomex core would have both a greater effect on the sandwich CME due to its β >>0 and a lesser effect due to E (Nomex) < E (Al). DuPont data [22] suggests Nomex shrinks 1.7% when dried, presumably from 50%RH where the moisture regain is about 4%. This implies a CME of 4250e-6/%M, typical of many organic materials. The modulus of Nomex is reported to be 4X that of Nylon 6-6 [22] which implies about 12 GPa. The shear modulus of an average density Nomex H/C cores is about 15 psi [23] or 10^{-4} GPa. Fig. 7 shows that the moisture-absorbing core now raises most predicted CME levels to above those of the facesheets alone. There is a wider range of CME values and the βx - βy trends with θ are reversed from the Al core case. A thicker core increases the spread of CME's at any expansion angle (except at 60 degrees). Fig. 8 shows characteristic behavior - nearly linear absorption with $\sqrt{t}$ and then continued absorption at longer times. With diffusivity derived with Eq. 13, Fig.9 shows a linear relation between microstrain on desorption and G using Eq. 15. Scatter between different samples can be attributed to variations in cell size and location relative to sample width. Predictions are given in Table I based on the limited measured and estimated values indicated.

Kevlar with Aluminum Core: The prediction in Table I is based on other results for woven Kevlar facesheet materials, where the range of $\beta x = \beta y$ = 280-360 (e-6/%M). Excellent agreement with predictions was obtained

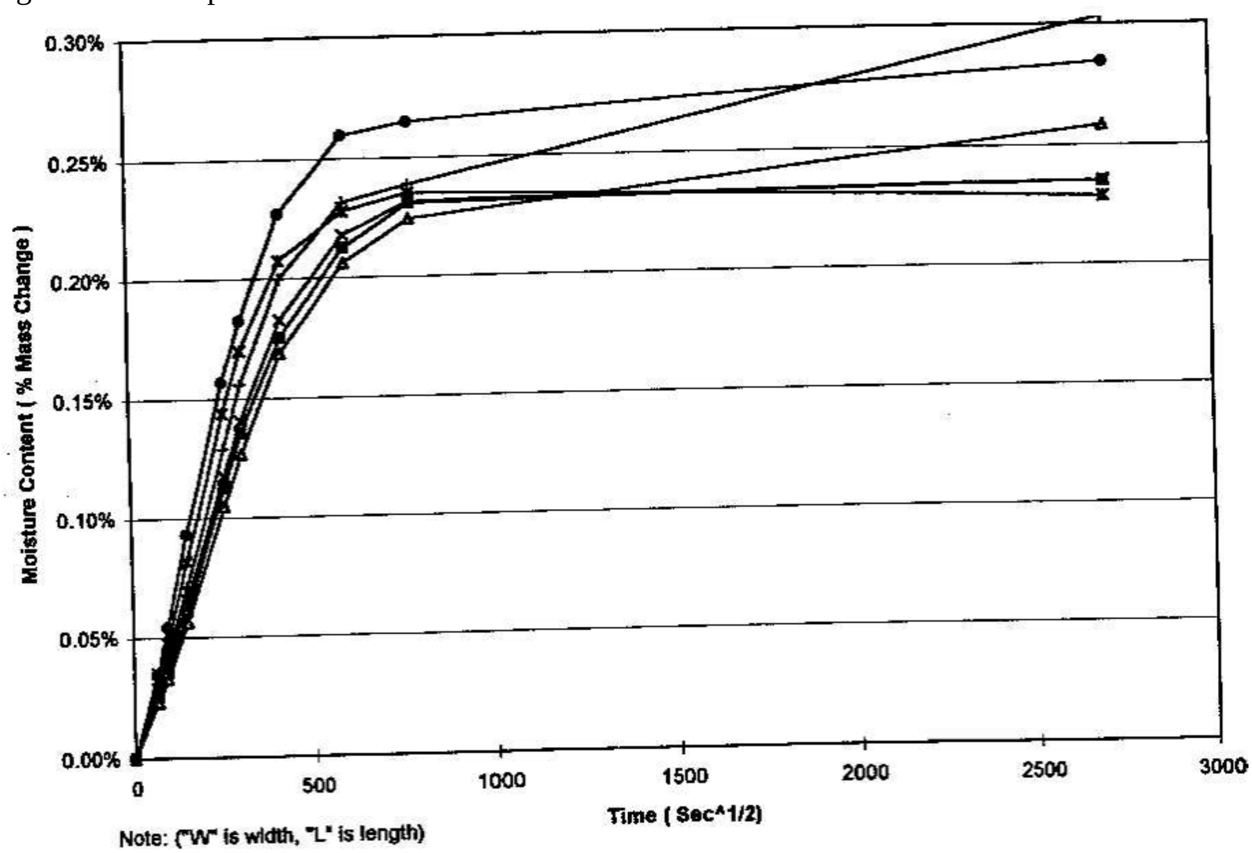

Fig. 6: Moisture Content Change of a M55J/954-3 Sandwich with Al Honeycomb between 75% RH and 0% RH at 26 ^{0}C. Data include both ribbon and cross ribbon direction samples.

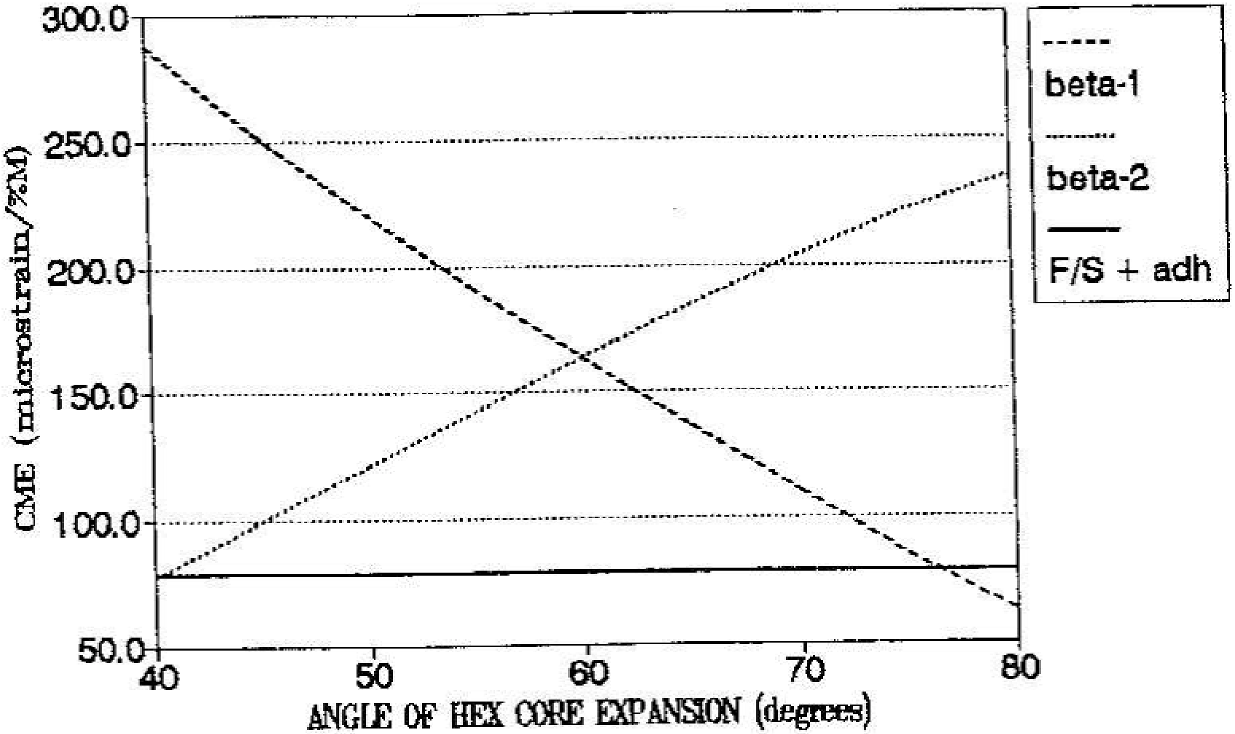

Fig. 7: Predicted CME variation with core expansion angle for a 50 mm NOMEX core and CFRP Facesheets.

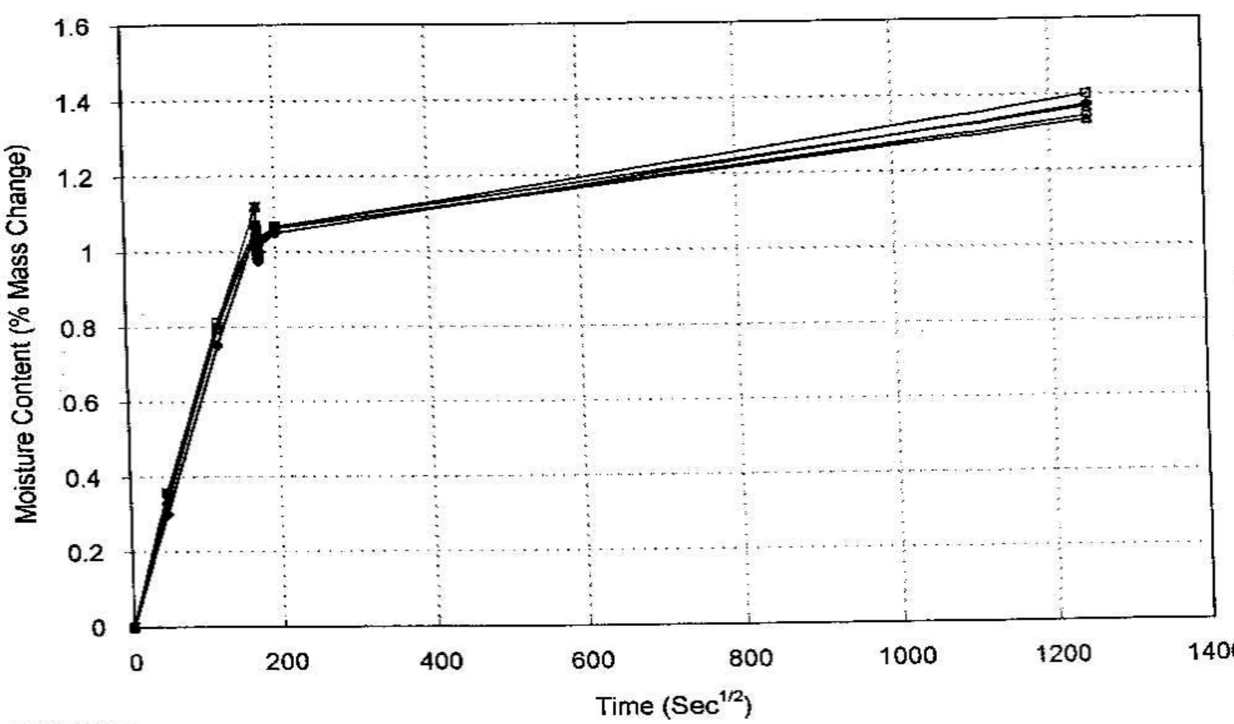

Fig. 8: Moisture Absorption of XN50/RS3 Facesheet with NOMEX Core Sandwich from 0 to 75% RH at 60 ^{0}C. (Five samples).

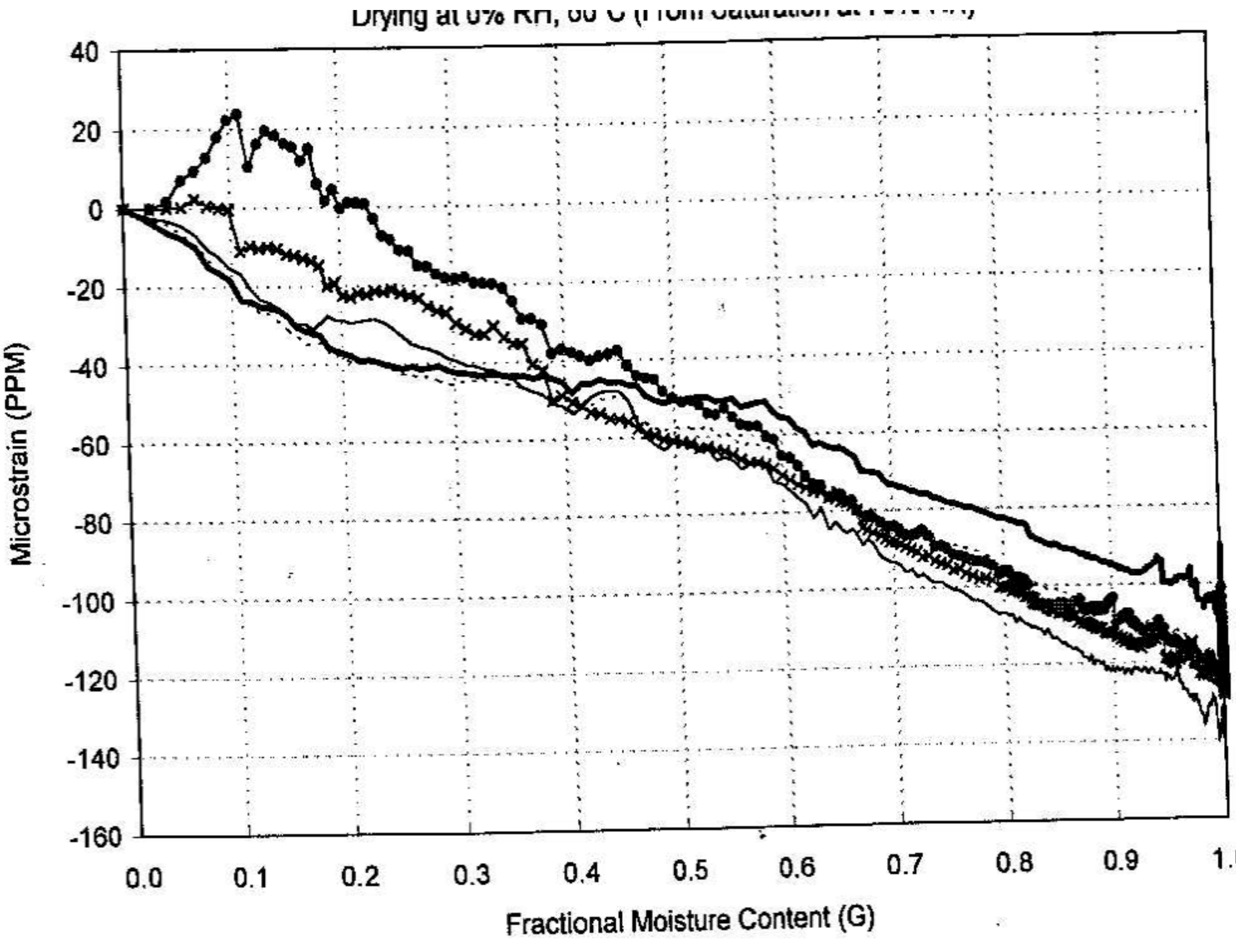

Fig. 9: Moisture Induced Ribbon Direction Strain for an XN50/RS3 NOMEX Core Sandwich Drying from Saturation at 75% RH to 0% RH at 60^0C.

UNSEALED SANDWICH PANELS

Panels were also tested with unsealed edges to obtain faster equilibration, especially at lower temperatures. This accelerates equilibration and in some cases no extrapolation of strain data is needed. Ab- or de-sorption can continue for very long times and a means to quickly determine the equilibrium values is needed. When initial diffusion appears Fickian (the slope of M (t) is linear with $\sqrt{t}$ e.g., Fig. 8), and also assuming that the facesheet strain dominates that of the sandwich, Eq. 15 suggests that $\varepsilon(t)$ vs. G(t) is bounded by $h<s<2h$. The first case implies that the core is no impediment to moisture transport to the inner facesheet surfaces. The latter is the edge-sealed case. Fig. 10 compares use of Eq. 13 and 15 with a three dimensional analysis (see below) and verifies this hypothesis. However, it also shows that moisture changes much faster than the strain, that is, Eq. 14 does not apply. None of these curves can then be used to extrapolate the strain to $t = \infty$ (G=1). Note that the data were only available to $\varepsilon_x = -34$ microstrain (when t = 29 days).

Aronhime et al [24] derived an expression for G (t) which can be used, via differentiation and multiple iterations of a matrix formulation, to obtain the 3-D diffusivities from short term absorption data:

$$G = 1 - [1 - (4/2a)(D_z t/\pi)^{0.5}][1 - (4/2b)(D_y t/\pi)^{0.5}][1 - (4/2c)(D_x t/\pi)^{0.5}] \quad (16)$$

The derived values of the diffusivities are inserted into the long term expression for G [25];

$$1 - G = (8/\pi^2)^3 \sum_{k=1}^{\infty} \sum_{l=1}^{\infty} \sum_{m=1}^{\infty} \{(2k-1)^2 (2l-1)^2 (2m-1)^2\}^{-1} \times$$

$$\exp\{-[(2k-1)^2 (\pi/2a)^2 D_z + (2l-1)^2 (\pi/2b)^2 D_y + (2m-1)^2 (\pi/2c)^2 D_x]\, t\} \quad (17)$$

Eq. 17 approximates the measured absorption curve if the acquired diffusivities are based on the entire curve. Dx and Dy tend to be two orders of magnitude greater than Dz. This helps to explain why the strain change lags the moisture change. The initial slope of M (t) vs. $\sqrt{t}$ is non-linear for facesheets which absorb substantial moisture, e.g. Kevlar laminates [24]. Consequently, the strain is assumed to depend on the three dimensional Dz only (for s = 2a). This is equivalent to Dx=Dy=0 in Eq. 17 for long term strain changes Fig. 10 shows that use of the three-dimensional Dz (from Eq.16) inserted in the 1D model of Eq. 15 with s=2a can generate a curve which can be extrapolated to infinite time (G=1).

TABLE I Predicted and Measured Results for Sealed Sandwich Panels

Measured properties			
Facesheet material	M55J/954-3	XN50/RS3	Kevlar 49
Facesheet Ply lay-up	[0/45/90/-45] s	quasi	woven 0/90
Core material	Al	NOMEX	Al
F/S ply thickness (mm)	0.0635	0.07	0.1397
F/S total thickness (mm)	0.508	0.28	0.279
Sample thickness 2a (mm)	10	6.86	25.96
Sample width 2b (mm)	38	38	76
Sample length 2c (mm)	177.8	152.4	254
Core thickness (mm)	9.9	5.8	25.4
Cell expansion angle (deg)	45	57	60
Core cell length (l) mm	7.1	8.4	9
Core cell width (d) mm	4.31	7.11	10.76
Core cell side (a) mm	2.79	3.8	2.79
Core foil thickness (t) mm	0.025	0.07	0.025

Estimated Values

Facesheet E1 (GPa)		351	335	70
E2 (GPa)		8.9	8	9
G_{12} (Gpa)		7.6	7	7
ν_{12}		0.3	0.2	0.3
β_1 (e-6/%M)	16	16	100	
β_2 (e-6/%M)	2000	2000	1500	
Adhesive thickness mm		0.025	0.025	0.25
Adhesive modulus (GPa)		3.45	3.5	3.5
Adhesive $\beta_1 = \beta_2$ (e-6/%M)		4000	4000	4000
Core Material Modulus GPa		69	12	69
Core Compressive Modulus (GPa)		-	0.138	-
Core Material $\beta_{1,2}$, (e-6/%M)		0	4250	0

Test Conditions

Edges	Sealed	Sealed	Sealed
Temperature (^{0}C)	60	60	24
Humidity Range (%RH)	0-75	0-75	0-52

Results (Measured)

Number of samples		6	10	3
Dz mm^2/s		1.88+/-0.3e-4	2e-6	2.5e-7
Sandwich Bx (ue/%M)		65.7+/8.7	84.8+/-8	225
By (ue/%M)	77.7+/-10.7	46.2+/-5.8	-	

Results (Predicted)

Sandwich Bx (ue/%M)	75	119	227
By (ue/%M)	79	108	-

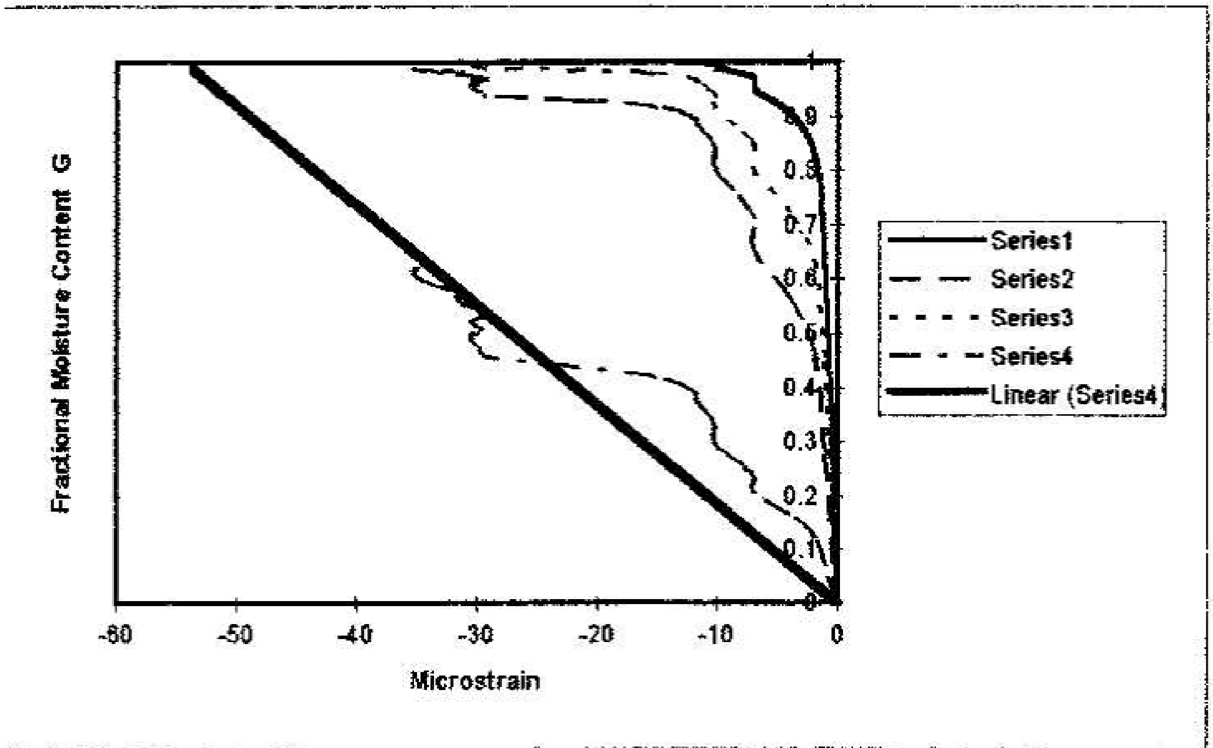

Figure 10. Desorption Microstrain ε_x vs. G of Sandwich Panel. Series 1; Dz =1e-7 via Eq. 13, 15, s=h, Series 2, same, s=2h, Series 3; 3-dimensional model, Dz=2e-6, Dx=2e-3, Dy=3e-4 mm^2/s, Series 4: Eq. 15 with Dz=2e-6, s=2a, fitted with linear regression curve.

DISCUSSION

Manufacturing variables such as core stretching and misalignment, adhesive wetting of the core, chemical processes such as leaching, post curing and ageing, moisture induced plasticization, and viscoelastic effects causing residual stress relief combine to make a predictive model very difficult. While ΔT is generally uniform throughout a sandwich structure we note that at any given time, a sandwich in a fixed relative humidity will have differing amounts of moisture in the facesheet, resin and core at any time. Moisture distribution will vary depending on whether the core is vented (pinholed) or unvented or if the core material absorbs moisture itself (e.g., NOMEX or KOREX). Nonetheless, the CTE and CME of laminates and the CTE of sandwich structures are predictable by the methods outlined, and the CTE of sandwich structures can also be readily measured.. The CME of sandwich panels is still difficult to measure unless tests are carried out to equilibrium times. While the method outlined above permits a good estimation of the CME, a more detailed model of the relation between moisture content change and and strain is needed. Measurements of strain to very long times at higher temperatures are also needed. We are currently employing microbalance technology and contactless strain sensors in a sealed environmental chamber to decrease test time and remove restrictions on instantaneous and simultaneous temperature and humidity changes. Work is also in progress on obtaining humidity/temperature cycling and aging effects and on determining coupling coefficients for hygrothermoelasticity studies.

CONCLUSIONS

With moisture absorbing honeycomb cores, such as Nomex, absorption or desorption strain can be twice as much in the ribbon direction of the core as in the cross ribbon direction.

Laminate theory with appropriate values for ply CME values and directional core stiffness values can be used to predict sandwich CME values. Predictions for fiber and cores which absorb moisture tend to give slightly higher CME values than are measured.

The core expansion angle is an important parameter, which must be determined after sandwich fabrication, since the core angle influences both CTE and CME. The theory of Inoue et al can help to account for its effects.

The ratio of $\beta x/\beta y$ (ribbon/cross ribbon CME's) is < 1 for Al cores and > 1 for NOMEX cores for core expansion angles below 60^o. These ratios reverse at $\theta > 60^o$. The ratios increase as the core thickness increases or as the core CME increases.

Measurement of the CME of sandwich structures requires extrapolation of data to infinite time. Considering the facesheet either open on both sides or sealed on one side bounds this extrapolation. Unlike laminates however, moisture change rates greatly exceed strain rates. In addition, moisture absorbing facesheets and/or cores exhibit non-Fickian diffusion behavior. A three dimensional analysis describes moisture changes. Strain is modeled by assuming the stiffer facesheets dominate. Extrapolation to equilibrium strain can be made with the 3D analysis assuming Dx=Dy=0.

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REFERENCES

1. Epstein G., The Composites & Adhesives Newsletter, T/C Press, Los Angeles Vol. 13, No.3, 1997, p3.

2. Wolff, E.G. "Polymer Matrix Composites: Moisture Effects and Dimensional Stability" International Encyclopedia of Composites Vol.4, Lee, S.M., Editor, VCH Publishers., New York, 1991, pp. 279-323.

3. Wolff, E.G., Chen, H., and Oakes, D.W. “Moisture Expansion of Honeycomb Sandwich Panels” 30th International SAMPE Technical Conferences, San Antonio, Texas, October 20-24, 1998, Vol. 30, pp105-116

4. Doxsee, L.E., Lee, W.I., and Springer, G.S., “Temperature and Moisture Induced Deformations in Composite Sandwich Panels.” Journal of Reinforced Plastics and Composites, Vol. 4,1985, pp326-354

5. Chamis, C.C., Aiello, R.A., and Murthy, P.L.N., “Fiber Composite Sandwich Thermostructural Behavior: Computational Simulation” Journal of Composites Technology and Research Vol.10, No. 3, 1988 pp93-99.

6. Ozaki,T., Miyahara,N. and Kabashima, S., “Thermal Stability and Electrical Loss Performance of Sandwich Panels for Space Antenna” Proceeding 40th Intl. SAMPE Symposium, May 8-11, 1995 pp1637-1645.

7. Inoue T., Kojima H., and Uemura M., “Effects of Production Error on CTE of Honeycomb Sandwich Panels” Proceedings 34th International Space Sciences and Technology Conference, 1990, pp. 72-73.

8. Nanjyo A., Mohri M., and Ishikawa T., “The Thermal Expansion of High Modulus Pitch-based Carbon Fiber Reinforced Composite Laminates” Proceedings 39th International SAMPE Symposium, April 11-14, 1994 pp. 541-550 .

9. Kabashima S., “Accurate Prediction of Thermal Deformation of Sandwich Panels Considering the Effect of Adhesive” Proceedings of the Eleventh International Conference on Composite Materials” Gold Coast, Australia, July 14-18, 1997, Scott, M.L. Ed. Vol. VI: Composite Structures, pp5149-5206.

10. Romeo G., Miraldi E., Ruscica G., Bertoglio F., Frulla G., and Ruvinetti G., “A New test Facility For Measuring the Coefficient of Moisture Expansion of Advanced Composite Materials” Journal of Composites Technology and Research. Vol. 14, No.4, 1992, pp225-230 .

11. J.F. Gilmore and C.A. Lloyd, “Assembly Suitable for Determining A Coefficient of Moisture Expansion of a Workpiece”, U.S. Patent #5,249,456 Oct. 5, 1993.

12. Cise D.M. and Lakes R.S., “Moisture Ingression in Honeycomb Core Sandwich Panels: Directional Aspects” Journal of Composite Materials, Vol. 31, No. 22, 1997, pp2249-2263.

13. Norris M.A. and Wolff E.G., “Moisture Expansion Measurement and Data Analysis Techniques for Composite Structures” Proceedings 40th International SAMPE Conference, Anaheim, CA, May 8-11, 1995, pp1867-1879.

14. Wolff, E.G., “Thermal Expansion of Asymmetrical Laminates” Thermal Conductivity 24/Thermal Expansion 12, Gaal, P.S., and Apostolescu, D.E., Editors, Technomic Publ. Co. 1999, pp351-367.

15. Norris, M., Oakes, D., and Wolff, E., “Thermal Expansion Measurement of Composite Structures” 40th International SAMPE Symposium, Anaheim, CA May 8-11, 1995, pp1855-1866

16. Herakovitch, C., “Mechanics of Fibrous Composites” J. Wiley & Sons, New York, NY, 1998, p191

17. “Flashbreaker” tape of one mil of polyester film coated with one mil of a cured silicone adhesive. AirTech Corp.

18 . ASTM E104-85 “Standard Practice for Maintaining Constant Relative Humidity by Means of Aqueous Solutions” (Section 14.02) 1985.

19. Shen, C-H., and Springer, G.S., “Moisture Absorption and Desorption of Composite Materials” Journal of Composite Materials Vol. 10, 1976 pp 1-17.

20. Wolff, E.G. “Prediction of Non-Mechanical Transient Strains in Polymer Matrix Composites” Proceedings of the Eighth International Conference on Composite Materials” Honolulu, HI July 1991, Tsai, S. and Springer, G.S., Editors, pp 32-S-1 –10.

21. Adda-Bedia,E., Han, W.S., and Verchery,G., “Edge Effects of the Moisture Diffusion in Polymer Matrix Composites with Cyclic Environmental Conditions” Fourth International Conference on Sandwich Construction, Stockholm, Sweden, June 9-11, 1998.

22. DuPont Fibers Brochure “Nomex Aramid” Bulletin #N-236 (1969).

23. DuPont, Brochures #H-14475, H-62627-1.

24. Aronhime, M.T., Neumann, S., and Marom, G., “The Anisotropic Diffusion of Water in Kevlar-Epoxy Composites” Journal of Materials Science, Vol. 22, 1987, pp. 2435-2446 .

25. Blikstad, M., Sjoblom, P.O.W., and Johannesson, T.R., “Long-Term Moisture Absorption in Graphite/Epoxy Angle-Ply Laminates” Journal of Composite Materials Vol. 18, 1984, pp. 32-46.