Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Numerical approach to calculate thermal expansion of honeycomb sandwich panel with composite face sheets

Shigenori Kabashima & Tsuyoshi Ozaki

Version of record first published: 02 Apr 2012.

To cite this article: Shigenori Kabashima & Tsuyoshi Ozaki (2000): Numerical approach to calculate thermal expansion of honeycomb sandwich panel with composite face sheets, Advanced Composite Materials, 9:4, 387-400

To link to this article: http://dx.doi.org/10.1163/15685510052000101

Adv. Composite Mater., Vol. 9, No. 4, pp. 387–400 (2000)

Numerical approach to calculate thermal expansion of honeycomb sandwich panel with composite face sheets

SHIGENORI KABASHIMA and TSUYOSHI OZAKI

Advanced Technology R&D Center, Mitsubishi Electric Corporation, Miyashimo1-1-57, Sagamihara, Kanagawa, 229-1195, Japan

Received 8 June 2000; accepted 30 June 2000

Abstract—The aim of this paper is to show an accurate method to predict thermal deformations of honeycomb sandwich panels having composite skins. First of all, some problems of the conventional method using the laminate theory are pointed out. In order to develop an effective predicting method, a model on detailed structure of a unit cell for sandwich panels is developed utilizing the 3D finite element method. A periodic boundary condition is introduced to the model to represent the repetitive structures of the sandwich panel. The effective elastic modulus of the cell foil is obtained from the result of an out-of-plane compressive test on the honeycomb core. The adhesives between skin and core is modeled by considering its shape and quantity. The difference between the CTE according to this model and the actually measured one is approximately 0.1×10^{-6}/K. The paper further attempts to explain the anisotropic character of the sandwich panel. The result of this analysis suggests that the direction-dependency of the CTE is underestimated with the fact that the effective elastic modulus at a portion where a ribbon is bonded with another one is different from the effective elastic modulus at a portion where the ribbon is on its own.

Keywords: Honeycomb sandwich panel; coefficient of thermal expansion; adhesives; finite element method.

1. INTRODUCTION

Honeycomb sandwich panels with thin PMC (Polymer Matrix Composite) skins are used to fabricate dimensionally stable satellite structures [1, 2]. Some systems such as high precision sensors require that the values of CTE of their structures be controlled with an error being within the range of 0.1×10^{-6}/K. It has been expected that recently developed pitch-based high modulus graphite fibers [3] are quite useful in realizing such highly dimensionally stable structures [4, 5]. In reality, however, this is not an easy task due to lack of a methodology to accurately predict thermal deformation of sandwich panels.

Though the laminate theory and the finite element method are utilized to calculate values of CTE of honeycomb sandwich panels [6–8], they do not satisfy the accuracy requirement. The reason why the error occurs in the calculation based on laminate theory is that the theory assumes that a honeycomb sandwich panel is a stack of homogeneous materials, and therefore details of the honeycomb core and the shape of adhesive are neglected. The error is further emphasized because sandwich panels used for satellite structures have very thin face skins, and the properties of the honeycomb core and adhesive have strong effects on the thermo-mechanical properties of the sandwich panels. Even when the finite element method is used, it is not easy to achieve sufficient accuracy because the models of the geometrical structures of sandwich panels are too simplified, and the effect of each constitutional material is not taken into consideration. Experimental validation of the values of CTE has not yet been carried out either.

This paper is to provide an accurate method of predicting thermal deformations of honeycomb sandwich panels based on the finite element method in which detailed structures of honeycomb sandwich panels are schematized and the effects of honeycomb core and adhesive are taken into account. Validation of the models is carried out by way of experimentation.

2. EXPERIMENTAL TEST

First of all, honeycomb sandwich panels with PMC skins were fabricated, and their values of CTE were measured. Table 1 shows the constitutional materials of the fabricated panels. The face skins consist of plain fabric of pitch based graphite fiber (K13A, Mitsubishi Chemical) and epoxy resin (934, Fiberite). Each of the face skins has an asymmetrical two-ply configuration of $[(0°/90°)/(\pm45°)]$. The sandwich panels as a whole are symmetrical. The thickness of each composite ply is 0.069 mm. The core is aluminum honeycomb core AL5056-3/8-0.0007 (HEXCEL) whose height is 9.35 mm. The skins and the cores are bonded with lightweight film adhesive FM-96U (Cytec) of which areal weight is 73.7 g/m^2 (0.015 psf). Table 2 shows properties of the materials. These data were obtained through experiments. The properties of the face skin shown here are those of $[(0°/90°)/(\pm45°)]$ laminate.

The adhesive is applicable in two different ways, as shown in Fig. 1a and b. Figure 1a shows the adhesive as applied uniformly all over the skin whereas Fig. 1b shows the adhesive as applied only on the edges of the walls of the honeycomb

Table 1.
Materials of the sandwich panels

Part	Material	Notes
Skin	K13A/934 $[(0°/90°)/(\pm45°)]$	0.069 mm/ply
Core	A13/8-5056-0.0007	height = 9.35 mm
Adhesive	FM96U	73.7 g/m^2 (0.015 psf*)

*Pound per square foot.

Table 2.
Material properties

Material	Young's modulus (GPa)	Poisson's ratio	Coefficient of thermal expansion (10^{-6}/K)
K13A/934 [(0°/90°)/(±45°)]	195	0.02	−1.0
A1 (5056)	70	0.30	23
FM96U	3.5	0.30	46

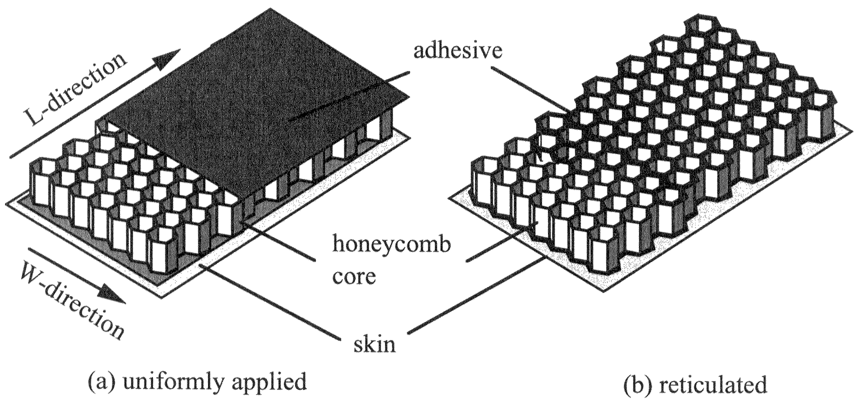

Figure 1. Shapes of adhesive.

core. The process of placing the adhesive as shown in Fig. 1b is called reticulation. Here, the reticulation was carried out by placing film adhesive on the core and then heating the film adhesive in an oven at the temperature of 120°C for 20 s to let the adhesive melt and condense. Three kinds of honeycomb sandwich panels have been fabricated with different bonding conditions as shown in Table 3. The number of stacked film sheets of the adhesive determines the amount of adhesive.

In order to evaluate the thermal deformation of sandwich panels, an original high precision CTE measurement system was developed. Figure 2 shows the configuration of the system. It consists of a temperature-controlled chamber and electro-optical cameras. Specimens are attached with two optical targets painted in black and white, and placed in the chamber. The cameras observe the optical targets and measure deformation of the specimens that occurs due to temperature changes. The distance between the two targets is 200 mm, in which there are 10 and 20 honeycomb cells in the L- and W-direction, respectively (L-direction and W-direction will be defined later).

In order to calibrate and validate the system, measurement was carried out for both zero expansive glass and graphite fiber reinforced plastic, of which values of CTE were known with the accuracy of 0.001×10^{-6}/K. As a result, it was found that the system is capable of measurement with the accuracy of 0.05×10^{-6}/K.

Table 3.
Bonding condition between skin and core

Specimen	Adhesive	
	Quantity	Shape
Panel #1	0.015 psf	reticulated
Panel #2	0.015 psf	uniform
Panel #3	0.030 psf	reticulated

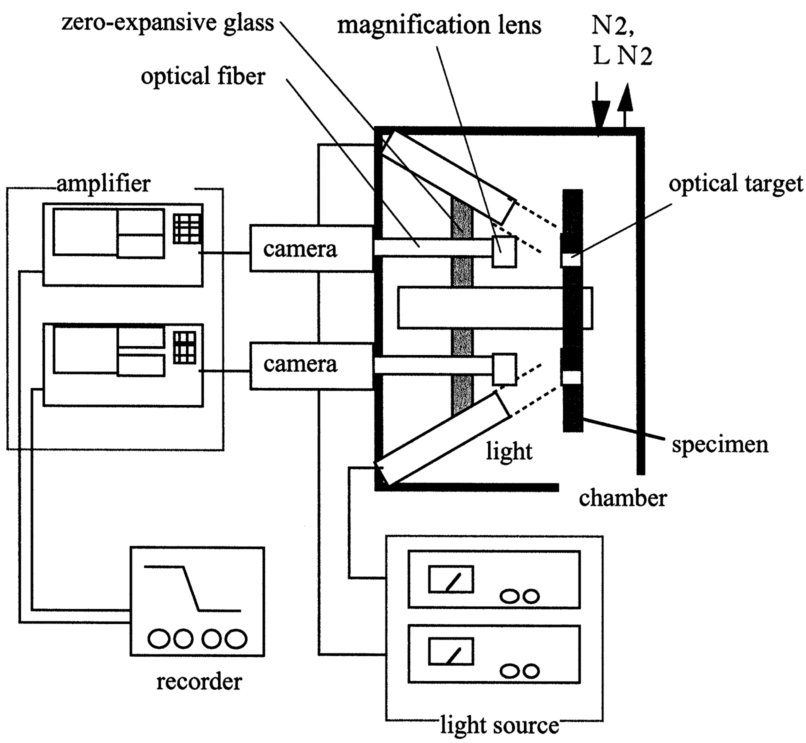

Figure 2. CTE measurement system.

Aluminum honeycomb core is fabricated from aluminum ribbons as shown in Fig. 3. The longitudinal direction of the ribbon and the vertical direction are respectively called L-direction and W-direction. It has been known that values of CTE of a honeycomb sandwich are direction dependent. Hence, three specimens were fabricated from each of panels #1–#3, and their average values of CTE were measured at temperatures of 0°C and 50°C for both the L-direction and the W-direction. Then, the average value was obtained for each specimen. Variation of measured values of each the specimens were smaller than 0.05×10^{-6}/K. Therefore, it can be concluded that these values have accuracy of 0.1×10^{-6}/K, when the

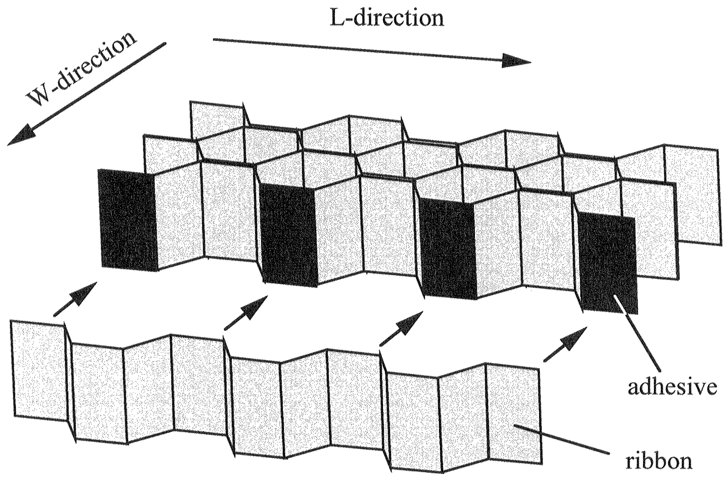

Figure 3. Structure of honeycomb core.

Table 4.
Measured values of CTE of the sandwich panels

Specimen	Measured CTE ($\times 10^{-6}$/K)	
	L-direction	W-direction
Panel #1 (0.015 psf, reticulated)	−0.52	−0.66
Panel #2 (0.015 psf, as placed)	−0.29	−0.37
Panel #3 (0.030 psf, reticulated)	−0.25	−0.36

measuring accuracy of the system is taken in to account. The results shown in Table 4 indicates the following:

1. The values of CTE in the L-direction are larger than those in the W-direction.
2. A decrease in the amount of adhesive decreases the values of CTE.
3. The reticulation process decreases the values of CTE.

3. FEM SIMULATION

3.1. Problems of conventional methods

In order to calculate the values of CTE of honeycomb sandwich panels by using the laminate theory, it is necessary to assume that the honeycomb core is a homogeneous material, such that the equivalent modulus of the homogeneous material can be obtained. Analytical [9] and experimental [6] methods have been proposed for this calculation. There is another approach to obtain the modulus of honeycomb core, in which the honeycomb core is schematized with the finite element method (FEM) and a tensile test is carried out virtually [10]. However, as has already been mentioned, such methods that introduce such simplifications are limited in the accuracy they can achieve. Therefore, it is expected that models that utilize the finite element method are useful in calculating thermal deformation of honeycomb sandwich panels accurately. In the present paper, the finite element model with a boundary condition that represents the repetitive structure of a honeycomb sandwich panel is studied. The model is created by using a general-purpose computer program so as to effectively calculate the thermal deformation of a honeycomb sandwich panel.

3.2. Periodic boundary condition

Thermal deformation of honeycomb sandwich panels cannot be calculated accurately by merely building a model for each unit cell, because there is a restrictive force among the unit cells that constitute the panels. On the other hand, it consumes a lot of time and computer resources to create a model that encompasses the whole structure of honeycomb sandwich panels. The homogenizing method [11] and the whole/local finite element method [12–15] which simulate repetitive structures such as woven fabric reinforced composites have been proposed. For example, boundary periodic boundary conditions based on the homogenizing method have been applied to the unit cell models [16, 17] so as to simulate the face skin buckling of honeycomb structure. In the present work, a periodic boundary condition to represent the repetitive structure of a honeycomb sandwich panel was utilized in the following manner.

Based on an assumption that the honeycomb sandwich panel is large enough relative to the unit cell, it can be assumed that all the unit cells are identical in terms of the deformation and stress condition. Therefore, the unit cell shown in Fig. 4 and its adjacent cells are symmetrical relative to the planes S1, S2, S3 and S4. Consequently, it can be assumed that the following boundary conditions represent the repetitive nature of the structure.

1. All nodes on plane S1 have the same x-coordinate.
2. All nodes on plane S2 have the same y-coordinate.
3. All nodes on plane S3 have the same x-coordinate.
4. All nodes on plane S4 have the same y-coordinate.

Finite element models in which there are n number of unit cells in both the L-direction and the W-direction were created based on the sandwich panels shown

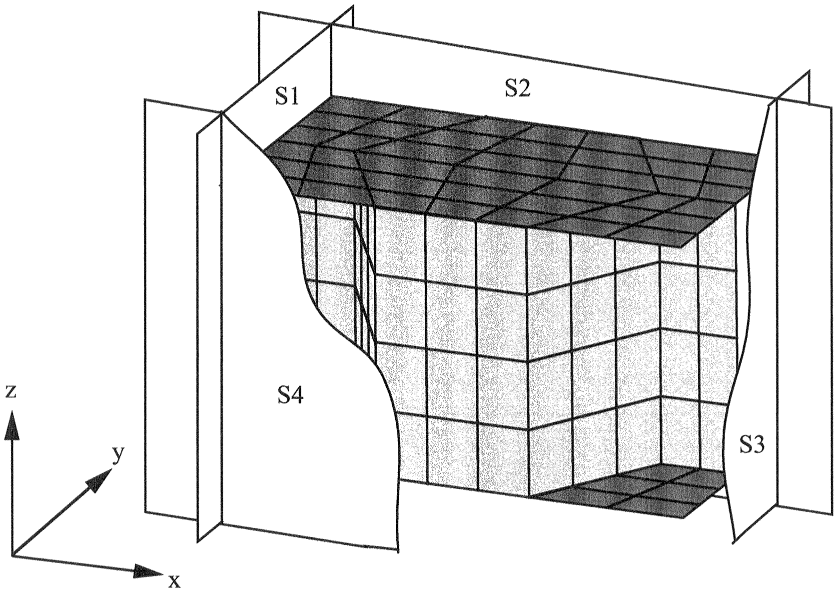

Figure 4. Planes of symmetry.

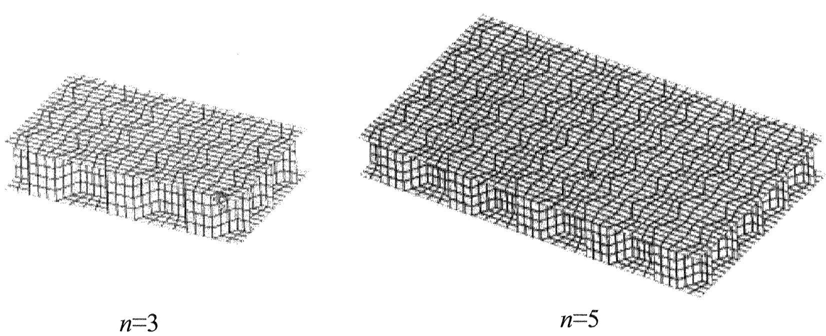

Figure 5. Multi cell models containing $n \times n$ cells.

in Table 1. The face skin and the cell foil were modeled as thin shell elements. Figure 5 shows examples of the models where $n = 3$ and $n = 5$. At the same time, the same panel was simulated using the unit cell model with the boundary conditions representing the repetitive structure. Figure 6 compares the values of CTE calculated from these models. The calculated values of CTE in the multi-cell model converge as n increases, and the convergent value coincides with the value calculated in the unit cell model. Thus, it was proved that the unit cell model with the boundary conditions accurately simulates the repetitive structure of a honeycomb sandwich panel. Further study was carried out to improve the unit cell model.

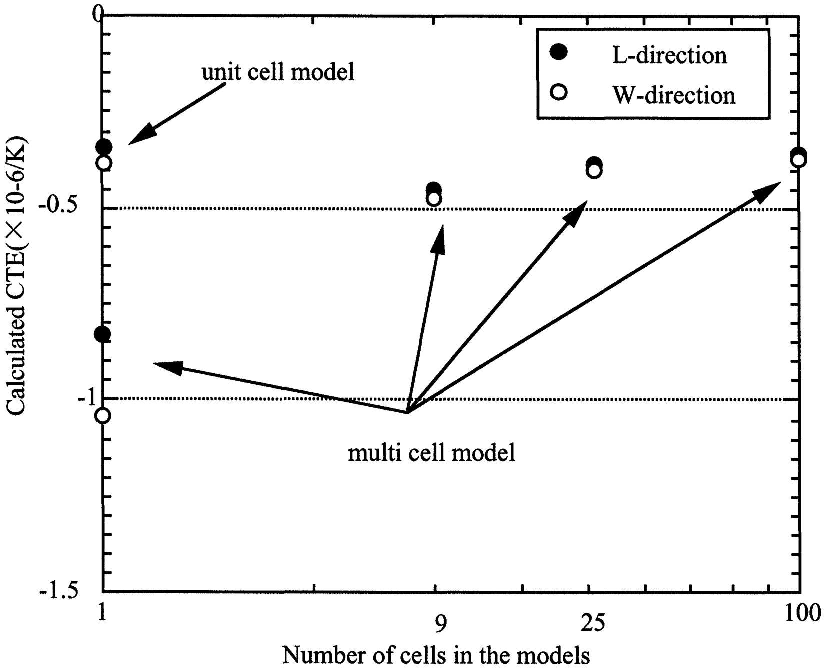

Figure 6. CTE values calculated from the unit cell model and multi cell models.

3.3. Modulus of honeycomb cell foil

In the preceding section, the rigidity of honeycomb cell foil was assumed to be the same as the Young's modulus of aluminum. However, detailed studies on the behavior of honeycomb core imply that this assumption is incorrect. It has been reported that the effective modulus of cell foils is considerably less because the cell foils are generally very thin and are subject to initial deformation [6]. Hence, the effective modulus has been obtained from an out-of-plane test of honeycomb core in the following manner.

Perpendicular rigidity of honeycomb core *Ecore(cal)* shown in Fig. 7 can be calculated as follows:

$$Ecore(cal) = Emat \times \frac{8t}{3a}. \tag{1}$$

Emat is the Young's modulus of the constituent material of the honeycomb. The initial deformation of the cell foil is neglected. However, actually measured out-of-plane rigidity *Ecore(msr)* is generally smaller than the calculated value *Ecore(cal)*. Figure 8 compares the *Ecore(cal)* and *Ecore(msr)* for several aluminum honeycomb cores that have different core sizes. The values of *Ecore(msr)* were provided by the honeycomb core manufacturer. According to the manufacturer, the values are measured according to MIL-STD-401 or ASTM standard. The sizes of the specimens for the measurement are 76.2 mm × 76.2 mm or 101.6 mm × 101.6 mm. The former size is for honeycomb core whose core size is smaller than 1/2 inch,

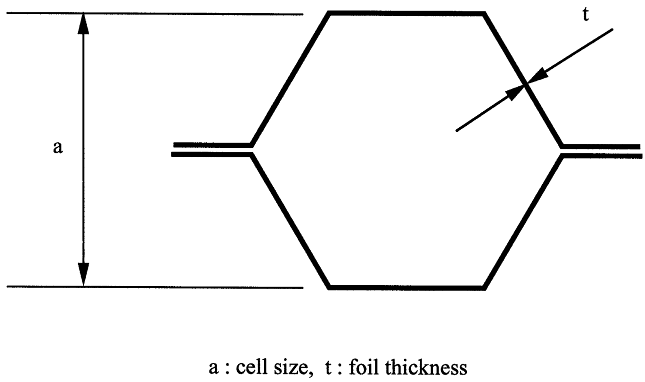

Figure 7. Dimensions of honeycomb core.

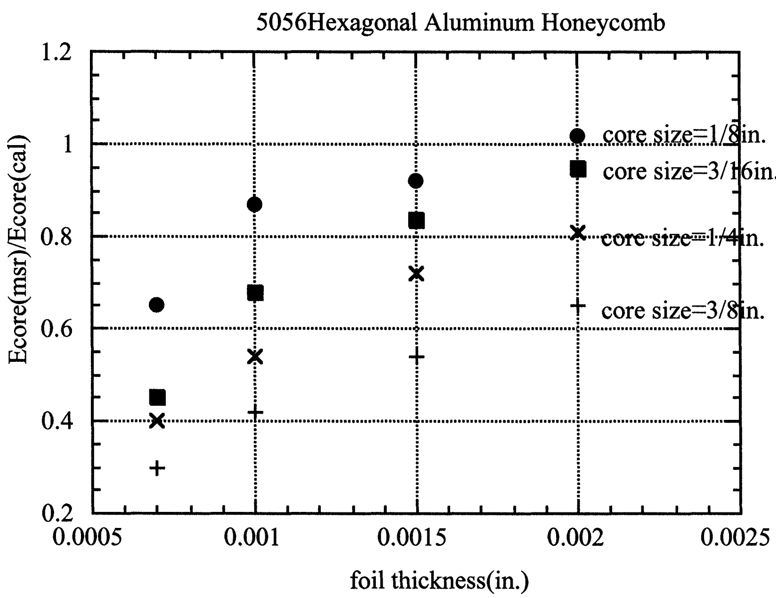

Figure 8. Measured and calculated perpendicular rigidities of honeycomb cores.

whereas the latter is for honeycomb core whose core size is equal to or greater than 1/2 inch. The height of all the specimens is 15.9 mm. Aluminum plates, of which the thickness is 0.5 mm, are glued to both sides of the specimens. A force perpendicular to the plane is applied to the specimen to obtain the initial inclination of the stress–strain curve, such that the rigidity of the panels in the perpendicular direction can be obtained. The larger the core sizes and the thinner the cell walls are, the larger the difference between the perpendicular rigidities of *Ecore(cal)* and *Ecore(msr)*. This is due to reduction of the effective modulus of the cell foil that occurs as a result of the initial deformation. Therefore, the effective modulus of the cell foil can be calculated as follows:

$$Efoil = Emat \times \frac{Ecore(msr)}{Ecore(cal)}. \tag{2}$$

The honeycomb core shown in Table 1 is made of aluminum 5056 of which Young's modulus is 70 GPa. Based on this value, *Ecore(cal)* is 0.348 GPa according to the equation (1). *Ecore(msr)*, on the other hand, is reported to be 0.105 GPa. Thus, $Efoil = 21.8$ GPa according to the equation (2).

As has already been mentioned, honeycomb cores are made into sandwich panels when the perpendicular rigidity of the honeycomb core is measured. This means that each face of the cell foil is a rectangular thin plate, of which four edges are fixedly supported. Hence, it is considered that the initial deformation has the same effect in the directions both perpendicular to and parallel with the panels. Therefore, the following study also assumes that the modulus of cell foil is reduced with the same rate of reduction for both perpendicular and parallel directions.

3.4. Modeling of skin/core adhesive

It is difficult to estimate the effect of adhesive between skin and core accurately by using the laminate theory. This is because the same amount of adhesive can give different effects on the thermal deformation of honeycomb sandwich panels depending on the shape of the adhesive, as mentioned earlier. Further study was carried out to simulate the effect of adhesive taking its shape into consideration.

When the reticulation process is not carried out in fabricating a honeycomb sandwich panel, the adhesive is applied uniformly over the face skin so as to form a layer in which the plane stress is generated according to the temperature change.

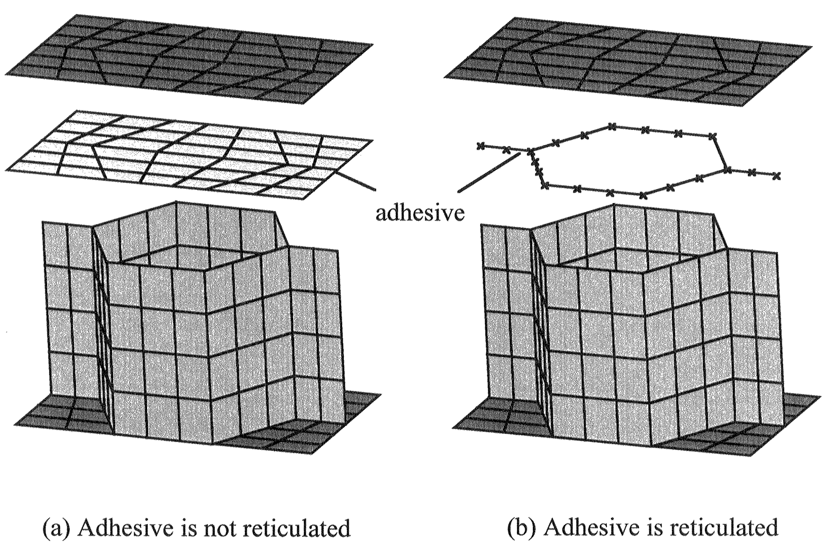

Figure 9. Developed FEM models.

Therefore, the adhesive was simulated as thin shell elements that are applied on the elements that simulate the skin. When the reticulation is carried out, the adhesive is applied only on the edges of the honeycomb core. In this case, the adhesive generates axial stress along the edges of the honeycomb core. Hence, the adhesive was simulated as bar elements. The thickness of the thin shell elements and the cross-sectional area of the bar elements were calculated from the volume of the adhesive applied. The volume of the adhesive was calculated from the weight and the specific gravity of the adhesive. Figure 9 shows the finite element models developed.

4. RESULT AND DISCUSSION

The coefficient of thermal deformation was calculated for three different kinds of honeycomb sandwich panels shown in Table 3 by using the newly developed finite element model. Calculation based on the laminate theory was also carried out for the purpose of comparison. The calculation based on the laminate theory was carried out only for the panel #2 which has the simplest structure. Table 5 shows the result. It can be observed that the difference between the value calculated using the newly developed finite element model and the actually measured value is within the approximate range of 0.1×10^{-6}/K, whereas the difference between the value and the actually measured value calculated using the laminate theory is $0.2–0.3 \times 10^{-6}$/K.

It was also observed that the newly developed finite element model tends to underestimate the anisotropic character of the honeycomb sandwich panels. In order to clarify the reason for this tendency, the effect of the adhesive between the honeycomb cells was also studied.

The amount of the adhesive between the cells was measured in the following manner. The aluminum core was dissolved in hydrochloric acid. The solution was filtrated such that the adhesive is extracted as a solid body. Then, the weight of the

Table 5.
Calculated values of CTE

Specimen	CTE values (FEM)		CTE values (laminate theory)	
	L-direction ($\times 10^{-6}$/K)	W-direction ($\times 10^{-6}$/K)	L-direction ($\times 10^{-6}$/K)	W-direction ($\times 10^{-6}$/K)
Panel #1 (0.015 psf, reticulated)	−0.57 (−0.05)*	−0.62 (+0.04)	—	—
Panel #2 (0.015 psf, as placed)	−0.26 (+0.03)	−0.30 (+0.07)	−0.07 (+0.22)	−0.07 (+0.30)
Panel #3 (0.030 psf, reticulated)	−0.40 (−0.15)	−0.44 (−0.08)	—	—

* ( ): difference from measured value.

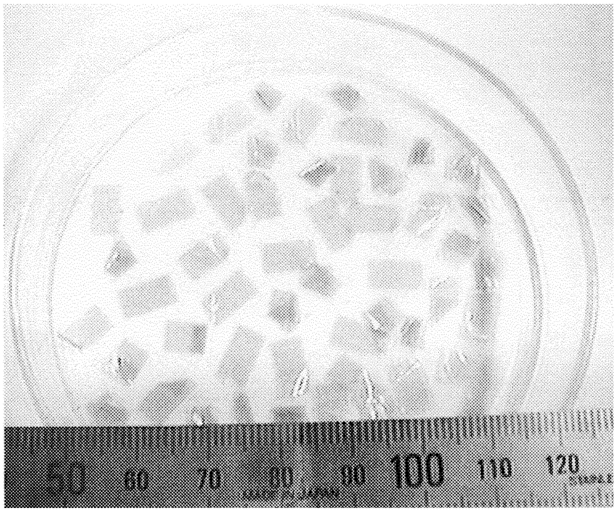

Figure 10. Inter-cell adhesive.

adhesive was measured. Figure 10 is a picture of the extracted adhesive. Thus, it became clear that the honeycomb core shown in Table 1 has on average 0.23 mg of adhesive at each adherent face.

The adhesive between the cells was simulated as thin shell elements in the finite element models. Although it was reported that the adhesive is made of epoxy resin, its mechanical properties were not known. Therefore, it was assumed that the mechanical properties of the adhesive between cells are the same as those of the adhesive between the skin and core. The calculation indicated that the effect of the adhesive between the cells is approximately 0.01×10^{-6}/K, which is a negligible value.

Thus, it has been found that the effect of the adhesive between the cells is negligible. Consequently, it is surmised that the reason why the anisotropy of the honeycomb sandwich plate is underestimated is as follows. As mentioned in Section 3, the effective modulus of the cell foil becomes less with a greater rate of reduction as the foil becomes thinner. This suggests that the effective modulus at a portion where a ribbon is bonded with another ribbon is higher than the effective elastic modulus at a portion where the ribbon stands on its own. In the newly developed method, however, the difference of the effective modulus at portions is not considered, and an average value is used instead. Hence, the effective modulus at a portion where ribbons are bonded is underestimated, whereas the effective modulus at a portion where the ribbon is on its own is overestimated. Besides, the ribbons bonded together mainly affect the properties of the panel in the L-direction, whereas the ribbon that is on its own mainly affects the properties of the panel in the W-direction. As a result, the calculated values of CTE are lower in the L-direction and higher in the-W direction than their actual values. Accordingly, it can be considered that these errors lead to the underestimation of the anisotropy of the property of the honeycomb sandwich panels. Though it is expected that consideration of the difference of the effective modulus of the cell foil at different portions will lead to a better result, further study still needs to be carried out before an actual improvement results. This study was not carried out at this time since an improvement would be only to a minor extent and it is difficult to actually measure the difference in the effective modulus at different portions.

5. CONCLUSION

An accurate and effective method of calculating the coefficient of thermal expansion of honeycomb sandwich panels with PMC skin was developed by using the finite element method. The method employs the following steps.

1. Build a finite element model which simulates the unit cell of the honeycomb sandwich panel. Use thin shell elements to simulate the skin and honeycomb core.

2. Apply periodic boundary conditions to represent the repetitive nature and the symmetry of the structure.

3. Obtain the effective modulus of the cell foil from the perpendicular rigidity of the honeycomb core.

4. Simulate the adhesive between the skin and the core by using the thin shell element or the bar element considering the shape of the adhesive.

It was proved that the calculated coefficient of thermal expansion and the actually measured value are within the range of approximate 0.1×10^{-6}/K from each other. Simplicity of the model and usage of an all-purpose program for the finite element analysis are the merits of this method. Further study was also carried out to explain the anisotropic character of the sandwich panel. It was found that the effect of the adhesive between the honeycomb cells is negligible. Thus, it was suggested that the direction-dependency of the CTE is underestimated due to the fact that the effective elastic modulus at a portion where a ribbon is bonded with another ribbon is different from the effective elastic modulus at a portion where the ribbon stands on its own.

REFERENCES

1. K. J. Dodson and J. E. Rule, Thermal stability considerations for space flight optical benches, in: *34th Int. SAMPE Symp.*, pp. 1578–1689 (1989).
2. F. Grimalde, G. Tempesta, F. Pastorelli and S. Pesciarelli, Development of dimensionally stable lightweight composite satellite antenna structures, in: *34th Int. SAMPE Symp.*, pp. 1590–1602 (1989).

3. P. W. Manders and F. C. Robertson, Advanced pitch fibre prepregs for space applications, *ESA SP-303*, 187–192 (1990).
4. S. O. Peck, High thermal conductivity graphite in space applications, *AIAA* **36**, 2931–2938 (1995).
5. B. P. Rice and A. S. Crasto, Characterization of a new composite material for space applications; P-100X HTS/954-2A, in: *40th Int. SAMPE Symp.*, pp. 1672–1684 (1995).
6. L. Scolamiero, Modeling of honeycomb core for sandwich CTE prediction, *ESA SP-321*, 427–430 (1991).
7. H. Groth, Thermal stability of sandwich reflectors, *ESA SP-243*, 133–139 (1985).
8. M. Marchetti and F. Morganti, Prediction of thermal expansion coefficients of sandwich using finite elements methods validated by experimental test results, *Acta Astronautica* **10**, 409–427 (1983).
9. T. Ozaki, N. Miyahara and S. Kabashima, Thermal stability and electrical loss performance of sandwich panels for space antenna, in: *40th Int. SAMPE Symp.*, pp. 1637–1646 (1995).
10. C. C. Chamis, R. A. Aiello and P. L. N. Murthy, Composite sandwich thermstructural behavior: computational simulation, *NASA TM-88787*, 370–381 (1986).
11. J. M. Guedes and N. Kikuchi, Preprocessing and post-processing for materials based on the homogenization method with adaptive finite methods, *Computer Methods in Applied Mechanics and Engineering* **83**, 143–198 (1990).
12. K. Woo and J. Whitecomb, Global/local finite element analysis for textile composites, *J. Compos. Mater.* **28**, 1305–1321 (1994).
13. J. Whitecomb, G. Kondagunta and K. Woo, Boundary effect in woven composites, *J. Compos. Mater.* **29**, 507–524 (1995).
14. C. Chapman and J. Whitecomb, Effect of assumed tow architecture on predicted moduli and stresses in plain weave compsites, *J. Compos. Mater.* **29**, 2134–2159 (1995).
15. K. Woo and J. Whitecomb, Three-dimensional failure analysis of plain weave textile composites using a global/local finite method, *J. Compos. Mater.* **30**, 984–1003 (1996).
16. N. Watanabe and S. Kimura, Thermal buckling behavior of very thin cfrp face in Al honeycomb sandwich plates for various lamination, *AIAA 39th SDM Conference* **39**, 2413–2422 (1994).
17. N. Watanabe, H. Sato and Y. Nishi, Thermal buckling behavior in Al honeycomb sandwich plates with very thin cfrp faces, *AIAA-97-1249* **38**, 2492–2501 (1997).