THERMAL DEFORMATIONS OF CARBON/EPOXY LAMINATES FOR TEMPERATURE VARIATION

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SUMMARY: Effects of anisotropy of thermal expansion properties on the thermal distortion of Carbon/Epoxy composite stiffner structures were investigated and analyzed. Coefficients of thermal expansion and elastic properties in the material principal directions were measured and characterized for temperature variation. By applying the characterized properties to the classical lamination theory, the spring-forward distortion of a L-section laminate was predicted. The spring-forward angles of L-section laminates of various angle plies were measured and compared with those predicted. Experimental results show that the process induced spring-forward of L-section laminate can be predicted quite well by using the computational method.

KEYWORDS: Thermal Deformation, Coefficient of Thermal Expansion, Carbon/Epoxy, Formulation of CTEs for Temperature Variation

INTRODUCTION

Carbon Fiber reinforced composites are widely developed and used as structural materials of the modern aircraft and spacecraft because of their high specific strengths, moduli, and design flexibilities. Furthermore, the low coefficient of thermal expansion(CTE) of carbon fiber composites can afford precision alignment and dimensional stability to aerospace structures. However, due to the anisotropy of materials, fiber reinforced composites have several problems during the manufacturing process. The process induced distortion brings about assembling problems of composite structures that need a precise dimension shape. This problem should be corrected to increase the performances of composite parts and to save cost and time consuming. To solve this problem, tool dimensions must be sized to correct the dimensional distortions occurring during the manufacturing process. Anisotropy of thermal expansion properties, residual stresses, chemical shrinkage and thickness change of plies affect the final shape of fiber reinforced laminate structures cured at elevated temperature [1,2,3,4,5]. Barnes et al.[1] showed that the difference of coefficients of thermal expansion and residual stress were the main sources of process induced distortion of curved laminates. Nelson[3] proposed a relatively simple set of analytical equations for the prediction of spring back in thermoset composite laminates, which included the effects of thermal dilatation strain, chemical shrinkage of the matrix, and residual stresses.
Yoon et al.[5] proposed computational model to predict a spring-forward angle of L-section AS4/PEEK thermoplastic composite laminates by incorporating the difference of thermal

expansion coefficients and frictional residual stresses effects . However, it has not been reported yet that the thermal distortion of thermoset composite structures were predicted by considering the changes of basic CTEs and moduli for temperature variation.
In this paper, the effects of anisotropy of thermal expansion properties on the process induced distortion of L-section Carbon/Epoxy thermoset composite structure were investigated. A computational method to predict the distortion of curved laminate due to the difference of CTEs was proposed. To verify the proposed computational method, the spring-forward angle changes of Carbon/Epoxy L-section were measured and compared with those predicted.

ANALYSIS FOR PROCESS INDUCED DISTORTION

Anisotropy of thermal expansion properties of a material induces thermal distortion when the temperature of the structure changes. Antisymmetric cross-ply laminates distort in cylindrical or saddle shape and laminates of unbalanced stacking sequence twist after cured in a flat mold at an elevated temperature. These distortions are shaped by the residual stresses occurred from the mismatch of CTE between plies. Even in the case of a symmetric stacking sequence, if a laminate is cured in a curved mold, the curvature of a laminate differs from the curvature of a mold after cure.

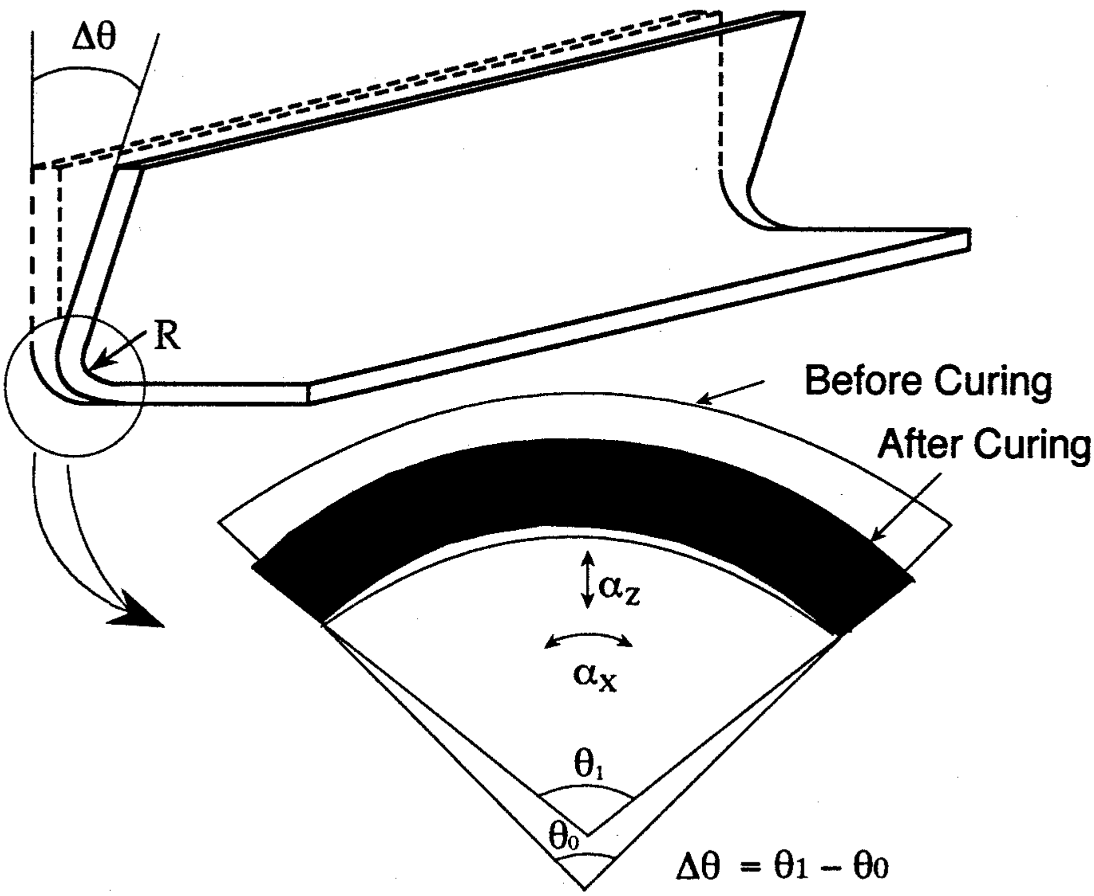

Fig.1 : Thermal Distortion of Curved Section of Anisotropic Material Structure

To describe the curvature change of curved section of an anisotropic material structure, O'Neill [2] showed that the arc angle change of a curved section can be expressed as Eqn 1 from a geometric analysis of a curved geometry as shown in Fig. 1,

$$\Delta\theta_{thermal} = \int_{T_f}^{T_0} \theta_0 \left\{ \alpha_z(T) - \alpha_x(T) \right\} dT \tag{1}$$

where θ_0 is the angle of the arc sector of the curved laminate, α_z and α_x are the CTEs in the through thickness direction and in the geometrical principal direction of the laminate plane respectively.
To predict the distortion due to the difference of CTEs precisely, it is important to characterize the change of the CTE for temperature variation accurately. It was reported that the CTEs of a polymer composite is dependent on temperature[5,6]. Barnes et al.[1] measured the CTEs changes of the $[\pm 45/0/90]_{2S}$ AS4/PEEK laminates for temperature variation and predicted the induced distortion angle of a L-section laminate by using the measured CTEs. In their method, CTEs should be measured experimentally for every laminate of different stacking sequence to predict its distortion angle of a curved section.
Yoon et al.[5] proposed analytical formulations to calculate the change of CTEs of various angle-ply laminates and used the calculated CTEs to predict the spring-forward angle of AS4/PEEK curved laminate structures.
In this study, an analytical procedure to calculate the CTE of a general stacking sequence laminate proposed by Yoon et al.[5] was used. As the temperature of composite materials changes, the thermal expansion strains of unconstrained laminate can be expressed as Eqn 2 using the classical lamination theory[7].

$$\begin{Bmatrix} \varepsilon_x^{0T} \\ \varepsilon_y^{0T} \\ \gamma_{xy}^{0T} \end{Bmatrix} = [A'] \begin{Bmatrix} N_x^T \\ N_y^T \\ N_{xy}^T \end{Bmatrix} + [B'] \begin{Bmatrix} M_x^T \\ M_y^T \\ M_{xy}^T \end{Bmatrix} \tag{2}$$

where $[A']$ and $[B']$ are matrices that are the parts of inverse of combined matrix of extension, coupling and bending stiffness, $\{N^T\}$ and $\{M^T\}$ are the thermal resultant forces and moments respectively. For temperature variation of ¥Ä1 the thermal strains of a laminate can be expressed as

$$\begin{Bmatrix} \varepsilon_x^{0T} \\ \varepsilon_y^{0T} \\ \gamma_{xy}^{0T} \end{Bmatrix} = \begin{Bmatrix} \alpha_x^{0T} \\ \alpha_y^{0T} \\ \alpha_{xy}^{0T} \end{Bmatrix} \Delta T \tag{3}$$

where $[\alpha^{0T}]$ are the coefficients of thermal expansion of a laminate.
From Eqn 2 and 3, the coefficients of thermal expansion of a laminate can be obtained as

$$\begin{Bmatrix} \alpha_x^0(T) \\ \alpha_y^0(T) \\ \alpha_{xy}^0(T) \end{Bmatrix} = [A'(T)] \int [\bar{Q}(T)]_k \begin{Bmatrix} \alpha_x(T) \\ \alpha_y(T) \\ \alpha_{xy}(T) \end{Bmatrix}_k dz + [B'(T)] \int [\bar{Q}(T)]_k \begin{Bmatrix} \alpha_x(T) \\ \alpha_y(T) \\ \alpha_{xy}(T) \end{Bmatrix}_k z\, dz \tag{4}$$

where

$$\begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}_k = [T_{\varepsilon}]_k^{-1} \begin{Bmatrix} \alpha_1(T) \\ \alpha_2(T) \\ 0 \end{Bmatrix} \tag{5}$$

α_1 and α_2 are the CTEs in the fiber direction and fiber transverse direction respectively. It should be noted that the values of $[A']$, $[B']$, $[\overline{Q}]$ and $\{\alpha\}$ are dependent on temperature. To obtain the CTEs of a laminate for temperature variation in Eqn 4, the basic mechanical and thermal expansion properties in the material principal directions need to be characterized for temperature variation.

CHARACTERIZATION OF MATERIAL PROPERTIES

Elastic Moduli and Poisson's Ratio for Temperature Variation

Elastic moduli and Poisson's ratios obtained from the tensile coupon tests at four different temperatures were fitted as linear functions of temperature for the convenience of simple formulations, which are shown in Fig. 2 and 3.

$$\begin{aligned} E_1 &= -0.0654T + 128.03 \quad (GPa) && (25^0 C \le T \le 140^0 C) \\ E_2 &= -0.0638T + 10.665 \quad (GPa) && (25^0 C \le T \le 140^0 C) \\ G_{12} &= -0.0339T + 5.3877 \quad (GPa) && (25^0 C \le T \le 140^0 C) \\ \upsilon_{12} &= -0.0005T + 0.4352 && (25^0 C \le T \le 140^0 C) \end{aligned} \tag{6}$$

where E_1, E_2, G_{12} and υ_{12} are the longitudinal, the transverse, the shear moduli, and Poisson's ratio, respectively.

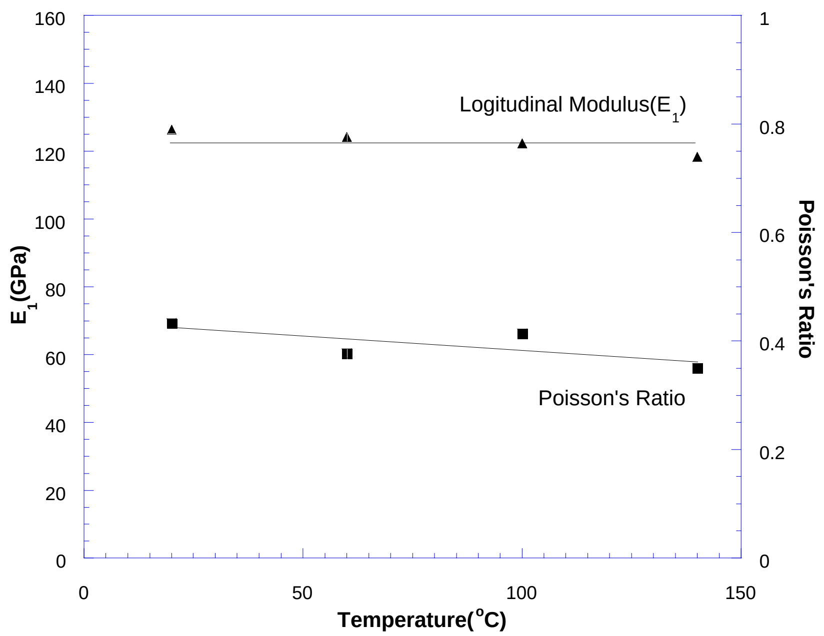

Fig. 2 : Logitudinal Modulus and Poisson's Ratio for Temperature Variation

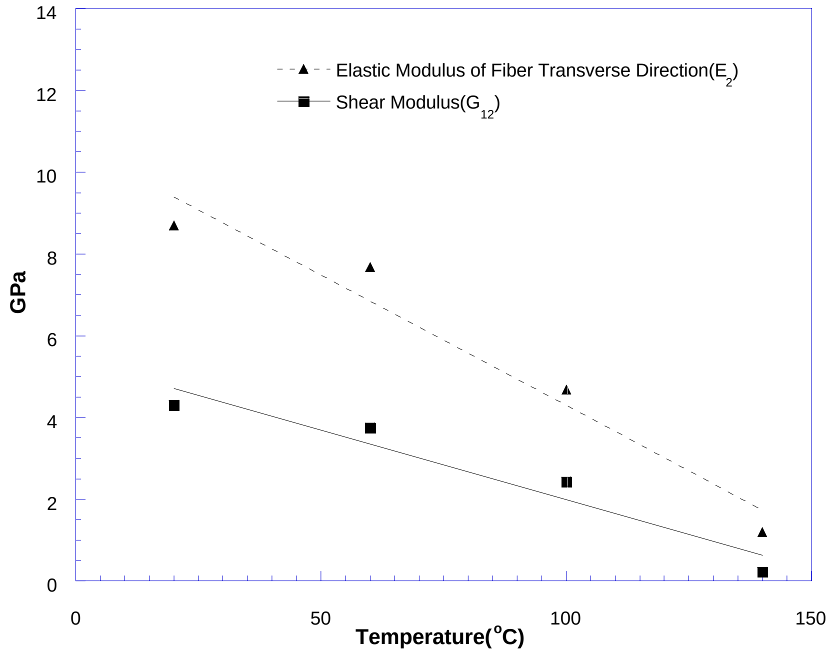

Fig. 3 : Transverse Modulus and Shear Modulus for Temperature Variation

Coefficients of Thermal Expansion for Temperature Variation

The composites reinforced with carbon fibers have a significant difference in CTEs between the fiber direction and the fiber transverse direction. This characteristic has been shown well by Barnes et al.[3] who measured the coefficients of thermal expansion of several PEEK composites and characterized the changes of coefficients of thermal expansion as functions of temperature in the range of 83^oK to 393^oK.

In this study, to measure the change of CTEs of a laminate in the in-plane material principal directions for temperature variation, specimens were cut by 20x50mm from $[0]_{8T}$ laminate. Two strain gages(WK-06-062AP-350, Micro-Measurement) for high temperature testing were bonded in the longitudinal and transverse directions along the centerline of a specimen. To measure the CTE in the out-of-plane direction Specimens cut by 50mm X 20mm from $[0]_{64T}$ laminate (thickness : 4.5mm) were used and strain gages were bonded in the through thickness direction. Thermal strains induced by temperature change were measured using strain gage measurement techniques used by Kim and Crasto[8].

The measured data in Fig. 4 show that CTE in the transverse direction doesn't change much below 80°C, but changes significantly after 80°C. In this study the measured CTEs in the longitudinal and fiber transverse directions were characterized as quadratic functions of temperature as shown in Fig. 4 for the convenience of formulation.

$$
\begin{aligned}
\alpha_1 &= (0.0003T^2 - 0.0355T + 2.0897)\times 10^{-6}(m/m/^0C) \quad (30^0C \le T \le 130\,^0C)\\
\alpha_2 &= (0.0041T^2 - 0.2254T + 32.23)\times 10^{-6} \quad (m/m/^0C) \quad (30^0C \le T \le 130\,^0C)\\
\alpha_3 &= (0.0037T^2 - 0.1496T + 32.78)\times 10^{-6} \quad (m/m/^0C) \quad (30^0C \le T \le 130^0C)
\end{aligned} \tag{7}
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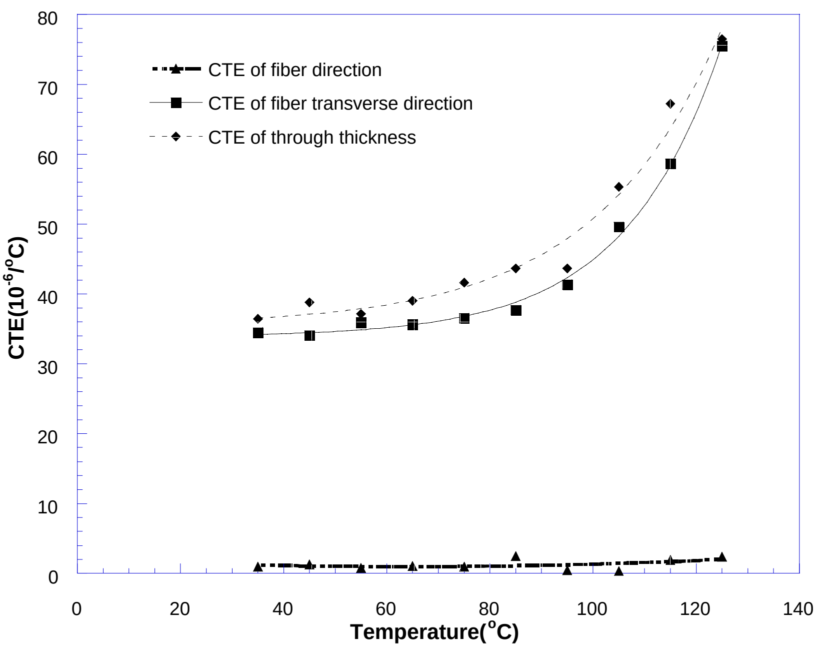


Fig. 4 : CTEs in the Material Principal Directions

VERIFICATION OF CTEs OF ANGLE-PLY LAMINATES

To verify the analytical formulations for the in-plane CTEs of general laminates, specimens, 20mm x 50mm in size, with $[\pm15]_{2S}$, $[\pm30]_{2S}$, $[\pm45]_{2S}$, $[\pm60]_{2S}$, and $[\pm75]_{2S}$ stacking sequences were prepared and tested for the measurement of in-plane CTEs. In Fig. 5 the measured CTEs of each $[\varphi]_{2S}$ specimen are compared with those predicted by using the analytical formulations. We can see those agreements between experimental data and predictions are quite good.

If CTEs obtained from the proposed formulations are used for an analysis of thermal deformation of a carbon fiber reinforced structure, it is expected that dimensional changes due to thermal deformations can be predicted more accurately than the cases of conventional linear analysis, which do not consider the changes of CTEs of laminates.

EXPERIMENTAL RESULTS AND DISCUSSION

L-section specimens (Fig. 6-a)of $[0]_{8T}$, $[\pm30]_{2S}$, $[\pm45]_{2S}$, $[\pm60]_{2S}$ laminates were selected to investigate the spring-forward behavior of Carbon/Epoxy composite laminate structures. Carbon/Epoxy laminates of L-section were manufactured by using an autoclave manufacturing process(Fig. 6-b). The angle changes of the manufactured specimens were measured at room temperature (25°C) by stamping the L-section on a reference paper of right angle mesh.

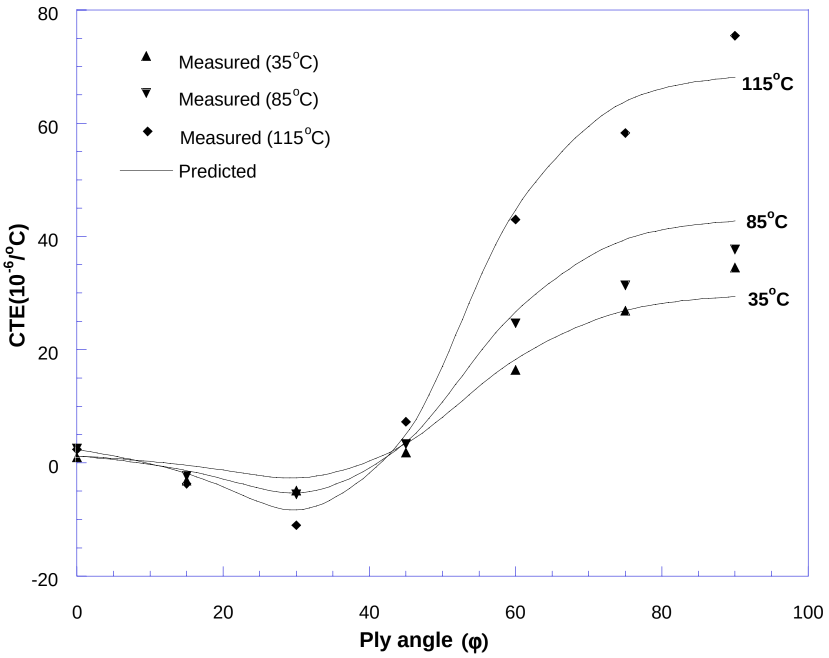
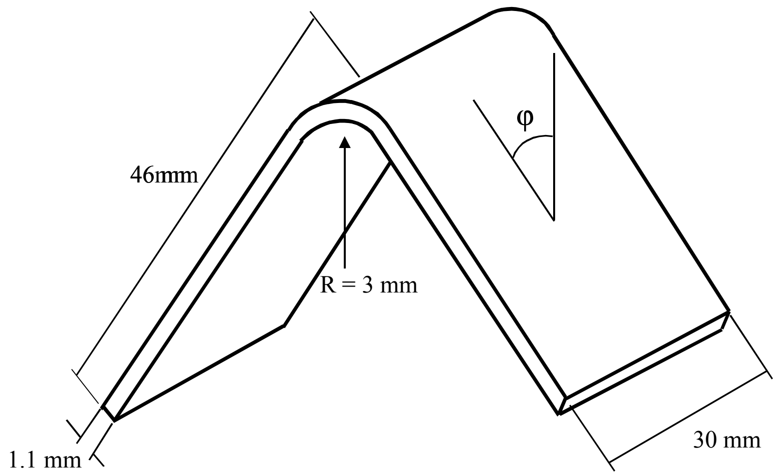


Fig. 5 : Measured and Predicted CTEs of $[\pm\varphi]_{2S}$ Laminate

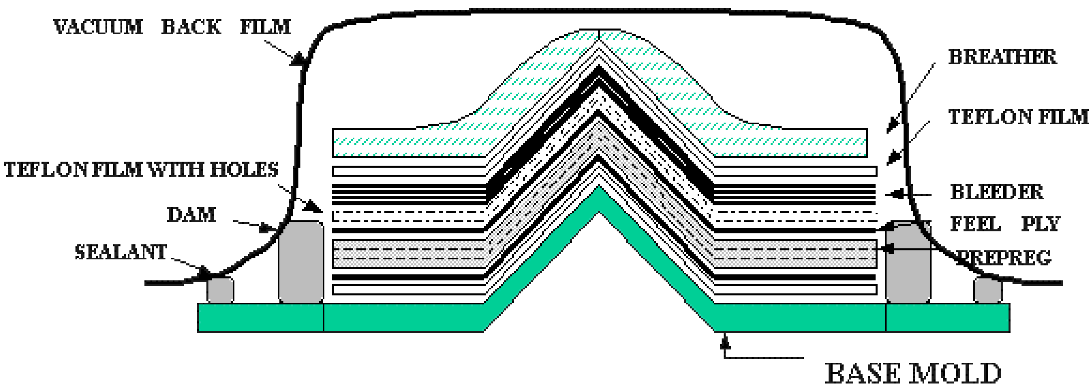
The Spring-forward angles of the various angle plies laminates were predicted by using the Eqn 1 to see the effects of thermal deformations. The measured data are compared with those predicted by the computational method in Fig. 7. The predicted values from the thermal analysis show that the the difference CTEs is the major sources of the process induced deformation of curved section laminates, even though the predicted values are still lower than the values from experiments. To predict the thermal distortion angle more precisely, other effects such as chemical shrinkage, residual stresses, thickness change of plies, visco-elastic and plastic deformation effect etc. must be included, as mentioned by Nelson and Cairns[3].

CONCLUSIONS

The effects of thermal deformation were investigated for L-section Carbon/Epoxy laminate structures. To see the effects of the difference of CTEs, the basic mechanical properties and thermal expansion properties of Carbon/Epoxy composite were characterized for temperature variation. By incorporating the characterized mechanical and thermal properties into the classical lamination theory, it was possible to obtain the change of the inplane coefficients of thermal expansion of a general stacking sequence laminate for temperature variation. The trend of spring forward angle of L-section laminate structures of Carbon/Epoxy was predictable by applying the calculated CTEs and chemical strains to the distortion models.



(a) L-section Specimen Shape



(b) General Lay-Up Structure

Fig. 6 : Specimen Dimensions and Autoclave Lay-Up Structure

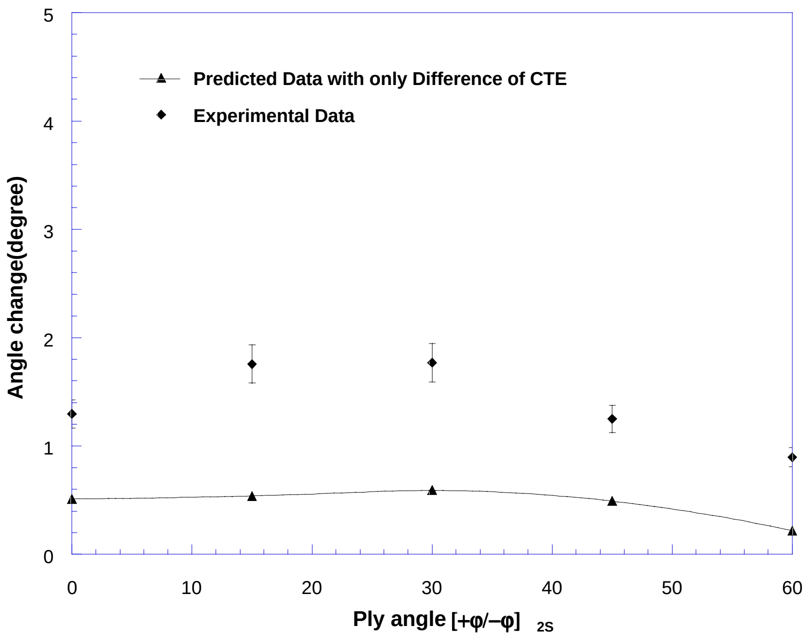


Fig. 7 : Comparison of Predicted Distortion Angles with Experimental Data

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