PREDICTION OF THERMAL PROPERTIES OF R-GLASS/EPOXY LAMINATES FOR TEMPERATURE VARIATION

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This paper focuses on the thermal properties of R-Glass/Epoxy laminate in response to temperature variations. The elastic properties and coefficient of thermal expansion in the material's principal direction were measured across the temperature range from room temperature to the cure temperature. These properties were then characterized as functions of temperature. Using the characterized properties and the principles of classical lamination theory, a method was proposed to predict the changes in the coefficient of thermal expansion for a general laminate subjected to temperature variations. The measured values of the coefficient of thermal expansion for laminates with varying angle plies were compared with the predicted values. The experimental results demonstrate that the proposed method accurately predicts the changes in the coefficient of thermal expansion for a general laminate under temperature variations. Additionally, an analytical formulation was proposed and validated to predict the changes in the coefficient of thermal expansion for R-Glass/Epoxy laminates subjected to temperature variations.

Keywords: *R-Glass/Epoxy laminate, Thermal properties, Analytical model, Thermal expansion, Experimental.*

1. Introduction

During long-term space missions, spacecraft are exposed to the harsh space environment, which can lead to degradation of structural materials over time. Graphite/Epoxy composites are considered ideal choices for structural materials in low Earth orbit applications due to their high specific stiffness, strength, and low coefficient of thermal expansion compared to conventional materials. For a polymer composite to exhibit advantageous properties, it is crucial to have optimal adhesion at the interface between the fibers and polymer matrix, and this adhesion must be maintained even when exposed to the environment to resist degradation. Textile technologies such as weaving, stitching, braiding, and knitting are being utilized to fabricate advanced composites with conformability, high quality, and integrated mechanical properties. The use of polymer composites has expanded in various advanced applications due to their favorable mechanical properties and low weight. However, [1, [2] composite structures in aircraft and other vehicles may experience exposure to heat radiation from sources like fire, lightning, repair procedures, and decontamination. [3] Consequently, such exposure can lead to a deterioration in mechanical properties without any visible indications. [4] investigated the coefficient of thermal expansion of graphite/epoxy composites, demonstrating that it is influenced by temperature and thermal cycles. A thermal cycle is defined as a temperature change from -70°C to 100°C and back to -70°C. They also observed that the thermal expansion coefficient decreased proportionally with an increase in thermal cycles after exposure to ultraviolet (UV) radiation, leading to a reduction in the strength and stiffness of the graphite/epoxy composite. [5] conducted a study using dynamic mechanical thermal analysis to determine the glass transition temperature (Tg) of a vinyl ester and E-glass/vinyl ester composite material fabricated through a composite pressure resin infusion system. [6] investigated the water absorption characteristics of unidirectional glass/epoxy composites. The specimens exposed to a humidity chamber often exhibited white crystalline deposits on their surfaces. The presence of ammonia was found to accelerate the hydrolysis of glass fibers, and the presence of ammonia within the laminate interior was expected to increase the rate of water absorption. In the case of the 90° fiber orientation, the rate of water absorption was slightly higher compared to the 0° fiber orientation laminate. [7]conducted a study on the effects of heat radiation on glass/epoxy laminates. The rapid delamination of the laminate resulted in a significant loss of shear strength and modulus due to the heat exposure. The flexural strength of the laminates was calculated using the formula S = 3(lu-lo)F/2bh^2. Additionally, a simple formula was introduced to estimate the approximate time it takes for visible defects to appear, given by Kxt/(I-Imin). The study revealed that there is no risk of invisible damage in freely supported laminates with unidirectional fibers. However, there is a risk of invisible damage in cross-ply laminates. [8] demonstrated that changes in the volume percentage of fibers do not result in significant changes in either the mechanical or thermal properties of the composite. The thermal

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expansion coefficient in the transverse direction exhibits a rapid increase above 50°C, as demonstrated by [9]. Damage observed on the upper surfaces of the beam was attributed to compressive failure, while damage on the lower surface was due to tensile failure. No indications of shear failure or crack initiation within the middle plane were found. [10] investigated the suitability of glass/epoxy composites for cryogenic applications. Cooling significantly affected the longitudinal strength of the composite, which increased by an average of 40% between 295K and 76K. The mechanical properties of the composite improved as the temperature decreased, with the performance strongly influenced by fiber orientation. [11] determined that thermal treatment did not have an impact on the interfacial properties or strength of the fibers after 1632 hours of exposure. [12] developed and utilized embedded strain gauge techniques to measure strains in angle-ply composite laminates during curing and thermal cycling. Strains recorded during the cooling phase of the curing cycle were consistent with those observed during subsequent thermal cycling, suggesting that residual stresses induced during curing are primarily caused by differential thermal expansion of the various plies. Composite materials have been widely developed and used as structural materials in modern aircraft and spacecraft due to their high specific strength, moduli, and design flexibility. Furthermore, carbon fiber composites exhibit a low coefficient of thermal expansion (CTE), which provides precision alignment and dimensional stability to aerospace structures. However, the anisotropy of fiber-reinforced composites presents several challenges during the manufacturing process. One of the common problems encountered is thermal distortion, which hinders dimensional stability and overall performance of the composite structures. [13] have highlighted the anisotropy of coefficients of thermal expansion, residual stresses, and chemical shrinkage as the primary factors causing shape distortion in fiber-reinforced composite structures after curing at elevated temperatures. Polymer composites are dependent on temperature, so it is important to predict the change in CTEs of R-glass epoxy composites for temperature variations. CTEs are measured experimentally for every laminate with different stacking sequences. For temperature variation, the characterization of basic properties of R-glass epoxy composites changes with respect to temperature. To replace the experimental process for obtaining CTEs, analytical formulations were proposed to predict the changes in CTEs of a laminate for temperature variations. It is significant because it provides a new and improved way to predict the CTE of R-Glass/Epoxy laminates. This is important because CTE is a critical property of composite materials, and its accurate prediction is essential for designing and using these materials in a wide range of applications. The proposed formulations offer several advantages over existing methods for predicting CTE. First, they are more accurate, especially at high temperatures and for laminates with complex stacking sequences. Second, they are more efficient, requiring less computational time and resources. Third, they are more versatile, and can be used to predict the CTE of laminates with a wide range of fiber volume fractions and fiber orientations. The objective of this research is to fabricate an aerospace-quality laminate with a layup sequence and fiber volume fraction (Vf) of 66% and glass transition temperature (Tg) of 140°C. The coefficient of thermal expansion will be measured at various temperatures, and a characterized equation will be derived as a function of temperature. Additionally, an analytical module will be developed to predict and validate the thermal expansion behavior of the laminate. The scope of this paper is to address the difference in coefficient of thermal expansions as a primary source of process-induced distortion in curved laminates during the manufacturing process. Considering the cost and time savings in manufacturing composite parts, it is crucial to appropriately size the tool dimensions, considering thermal distortion and residual stress induction. This is particularly important to achieve dimensional stability in modern aircraft and spacecraft subjected to thermal cycling. The methodology adopted for this study involves two phases of composite material manufacturing: fabrication and processing. Thermo-mechanical analysis software is employed to obtain temperature variation plots at a constant heating rate. These plots assist in understanding the thermal behavior of the composite material during the manufacturing process.

2. Analytical formulation

2.1 Characterization of basic properties

To investigate the changes in elastic properties of R-Glass/Epoxy composite (volume fraction: 60%, Tg: 110°C) under varying temperatures, laminates of different orientations ([0]8T, [90]16T, and [±45]2S) were manufactured using the autoclave method. For high-temperature testing, coupon specimens were prepared for tensile tests, and strain gauges (Micro-Measurement) were bonded along the longitudinal and transverse directions along the centerline of each specimen.

Figure 1: depicts the schematic of the testing system used in the experiment. Uniaxial tension tests were carried out utilizing the closed-loop servo hydraulic MTS 810 machine. Illustrate the schematic of the testing system. Uniaxial tension tests were conducted using the closed-loop servo hydraulic MTS 810 machine at temperatures of 20°C, 60°C, 100°C, and 140°C. The specimen was gripped by MTS hydraulic grips located outside

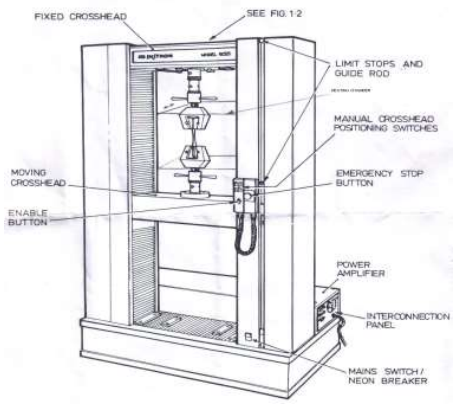

Fig. 1

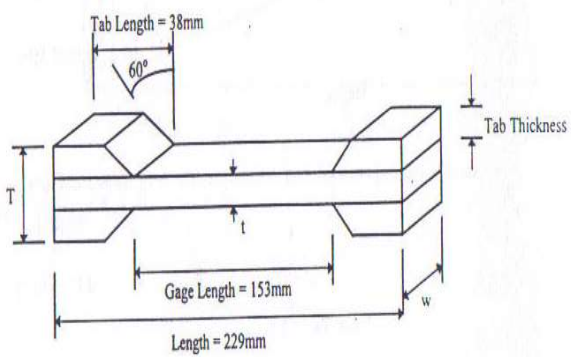

Fig. 2

a small heating chamber designed to regulate the temperature of the gauge section.

Figure 2: displays the test specimen used in the study, with a total length of 229 mm and a gage length of 153 mm. To prepare the bonding surfaces for the end tabs of the panel, follow the steps at first sand the regions of the panel where the end tabs will be bonded using medium-fine sandpaper. Use +45 motions while sanding the bonding surfaces. Next Utilize a wire brush to remove any loose particles from the crevices.

Clean the surface with acetone until all loose glass fibers are completely removed. Similarly, for the end tubes, follow the same procedure of sanding and cleaning the bonding surfaces as done for the composite panel. Next, proceed with the adhesive application using the following steps, mix the components of the adhesive. For room temperature and lower temperature applications, Hysol 934 or 929 can be used.

Next apply the adhesive on both bonding surfaces, ensuring proper coverage. Place the panel with the end tabs into an end tab fixture and allow sufficient time for the adhesive to cure under pressure in the fixture. After the bonding process, measure the cross-sectional dimensions of the test specimen to ensure accuracy. To determine specimen strains, electrical resistance strain gauges can be used. It is recommended to use foil gauges with a resistance of 350 ohms and a gauge length of 3 to 6 mm. Typically, two gauges, one in the longitudinal direction and one in the transverse direction, are bonded to the specimen. The below table provides information about the properties of three different types of fiber orientation: 0°, 90°, and [+45]. The table includes the width, number of plies, length, type, and thickness of each fiber orientation.

2.2 Proposed analytical formulation

Basic properties are obtained from experiments where fitted as linear functions of temperature for the convenience of formulations, which are shown in below figures.

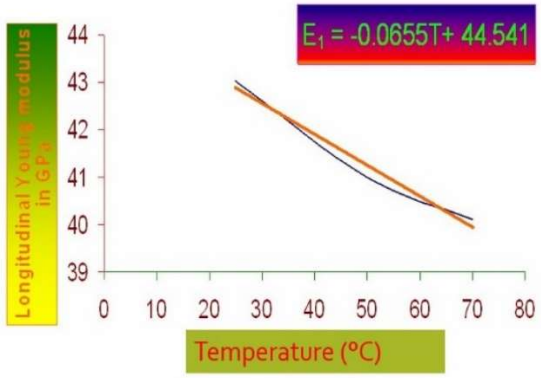

Fig. 3 - Longitudinal young's modulus as function of temperature

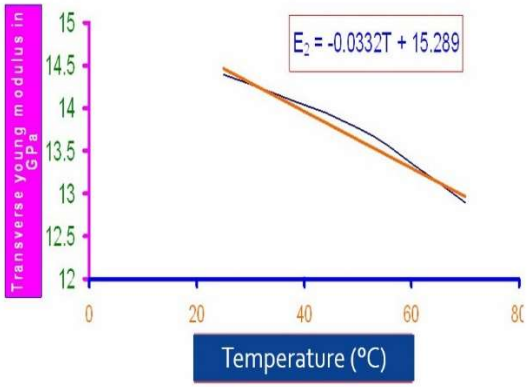

Fig. 4- Transverse young's modulus as function of temperature

Table 1

Fiber Orientation Properties

Fiber Orientation	Width, mm	Number of plies	Length, mm	Type	Thickness mm
0°	12.7	20	229	Symmetric	2.8
90°	26	20	229	Symmetric	2.8
[±45]	26	20	229	Symmetric	2.8

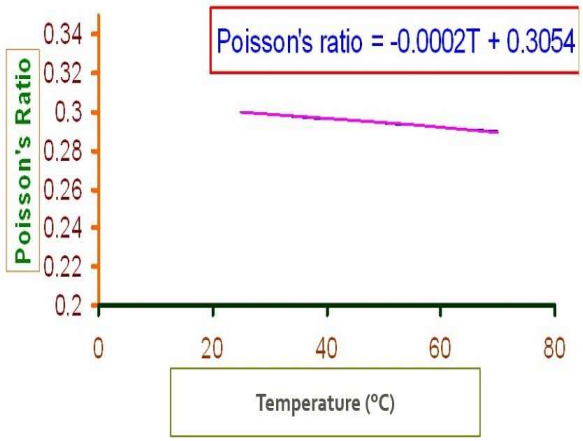

Fig. 5 - Poisson ratio as function of temperature

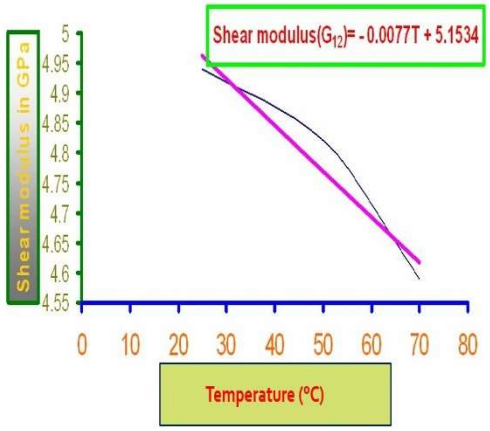

Fig. 6 - Shear modulus as function of temperature

Where E_1, E_2, G_{12} are the longitudinal, the transverse, the shear modulus, respectively as function of temperature. Transformation Formulae of Unit directional in to Angle Ply Elastic Properties by using classic laminar theory

$$[\overline{Q}] = [T^{-1}][Q][R][T][R^{-1}]$$

Where [T] is transformation matrix, [R] is the Reuter matrix and [Q] is reduced stiffness matrix. from this equation the co-efficient of thermal expansions for unidirectional laminate are calculated by using longitudinal, the transverse, the shear modulus and Poisson ratio as functions of temperature. Proposed analytical formulations to predict the changes in the thermal expansion coefficient of R-Glass/Epoxy laminate for temperature variation by using basic mechanical properties as function of temperature. The values of thermal expansion coefficient of laminates [±30]5s, [±45]5s and [±60]5s are calculated by using proposed analytical formulations.

3. Experimental investigations

In order to investigate the coefficient of thermal expansion of a laminate in the material principal directions for temperature variation, laminates of R-Glass/Epoxy composite (specifically T300/913 with a fiber volume fraction of 60% and a glass transition temperature of 140°C) were manufactured using the autoclave method. Specimens measuring 20 x 10 mm were cut from the unidirectional [0] 20T laminate. The experimental technique employed for this investigation is the thermo-mechanical analyzer (TMA), which measures the changes in length or thickness of a specimen as a function of temperature. The TMA is a widely used technique and offers the advantage of being able to use small specimen sizes. Using the TMA, the changes in dimensions of the laminate specimens can be measured accurately as the temperature is varied. This allows for the determination of the coefficient of thermal expansion in the material's principal

Table 2

Proposed analytical formulations for [±30]5s, [±45]5s and [±60]5s laminates

	[±30]$_{5S}$ LAMINATE	**[±45]$_{5S}$ LAMINATE**	**[±60]$_{5S}$ LAMINATE**
For 35° C	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}5.49\\ 18.5\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}11.18\\ 11.18\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}13.3\\ 13.3\\ 0\end{bmatrix} x10^{-6} m/m/°c$
For 40° C	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}5.52\\ 19.625\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}11.214\\ 11.214\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}19.56\\ 5.80\\ 0\end{bmatrix} x10^{-6} m/m/°c$
For 50° C	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}5.78\\ 21.617\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}12.09\\ 12.09\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}21.5\\ 5.819\\ 0\end{bmatrix} x10^{-6} m/m/°c$
For 60° C	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}6.01\\ 23.42\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}12.5\\ 12.5\\ 0\end{bmatrix} x10^{-6} m/m/°c$	$\begin{Bmatrix}\alpha_x^0(T)\\ \alpha_x^0(T)\\ \alpha^0_{xy}(T)\end{Bmatrix}=\begin{bmatrix}22.8\\ 5.9\\ 0\end{bmatrix} x10^{-6} m/m/°c$

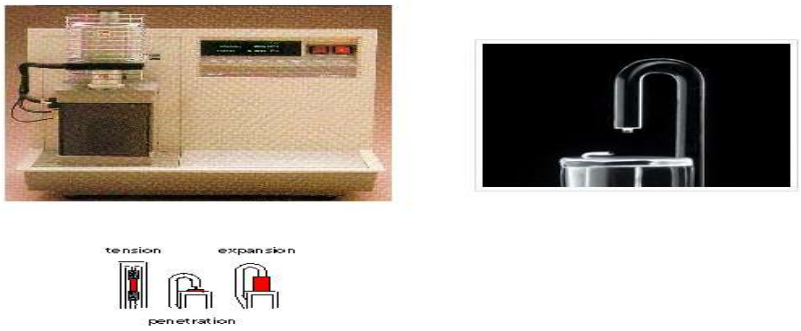

Fig. 7 - Thermo Mechanical Analyzer (TMA)

directions. TMA Apparatus to measure to expansion coefficient and strain, during the TMA testing, the test specimen was placed in a Thermo Mechanical Analyzer (TMA) under a load of 0.05N. The TMA apparatus used in the experiment was specially imported from England.

The TMA offers different measurement modes, such as penetration and bending. In this case, the aim was to observe the deformation of the sample under the applied load. For penetration experiments, a ball-point probe is commonly used. Initially, only a small area of the probe comes into contact with the sample. As the sample softens, the probe gradually penetrates deeper into the sample, allowing for the measurement of its deformation. TMA measurements are typically conducted with a dynamic temperature program, with a heating rate ranging from 5°C/min to 10°C/min, although 5°C/min is commonly used. One of the frequently performed TMA measurements is the determination of the glass transition temperature. At the glass transition, the expansion coefficient of the sample exhibits a significant increase, resulting in a steeper slope on the dilatometer curve. The first heating curve of a new sample often shows anomalies at the glass transition, which can be attributed to effects like volume and stress relaxation, drying effects, or foreign particles (such as dust) penetrating the softened sample. In penetration measurements, the ball-point probe directly rests on the sample surface and penetrates further into the sample at the glass transition. However, with highly filled polymers like carbon fiber reinforced composites, the probe may encounter difficulty in penetrating the sample due to its high stiffness.

4. Results and discussion

4.1 Experimental verification of [±30]$_{5s}$ laminate

A dummy template made from a metal plate was used as a base for the experiment. From this template, a laminate was created using R-Glass/Epoxy unidirectional prepreg. The laminate consisted of [+30] layers, where the fibers were oriented at an angle of 30 degrees to the longitudinal direction. The layers were arranged in a symmetric manner, alternating between +30 degrees and -30 degrees, and a total of 20 layers were used. The fabrication of the laminate was performed using the autoclave method. After the laminate was fabricated, test specimens were cut from it. These specimens were then subjected to TMA testing to determine the thermal expansion coefficient experimentally. Longitudinal thermal expansion coefficient and strain as function of temperature for [±30]$_{5s}$ laminate,

Figure 8, the glass transition temperature for the longitudinal direction and the service limit curve is shown. Figure 9, provides the thermal expansion coefficient at different temperatures in its principal direction for the longitudinal direction.

Figure 10, the glass transition temperature for the transverse direction and the service limit curve is shown. Figure 11, provides the thermal expansion coefficient at different temperatures in its principal direction. Characterized Equations

- α_1 = - 0.0068T+5.6879
- ε_1 = 0.1062T-3.6995
- ε_2 = 0.2178T-7.606
- α_2 = 0.0008T^2 -0.0783T+20.528

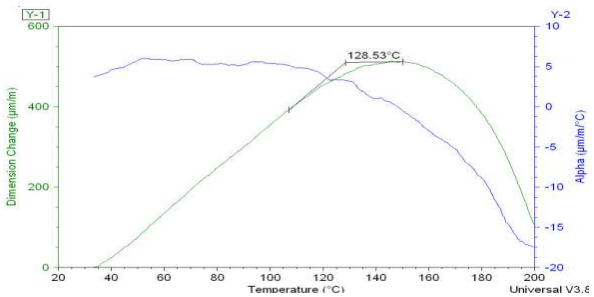

Fig.8

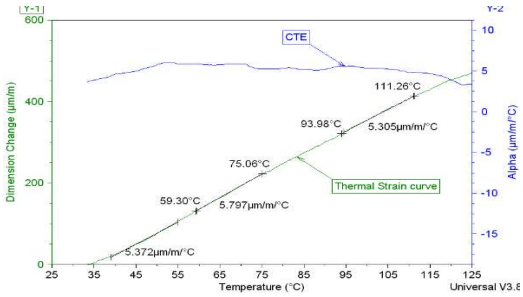

Fig.9

Fig. 8 and Fig. 9 - Longitudinal thermal expansion coefficient and strain as function of temperature for [±30]$_{5s}$ laminate.

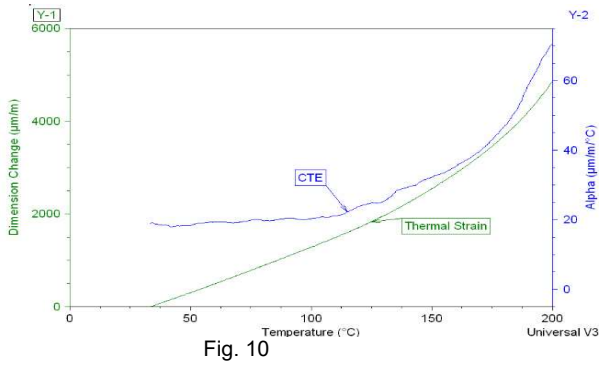

Fig. 10

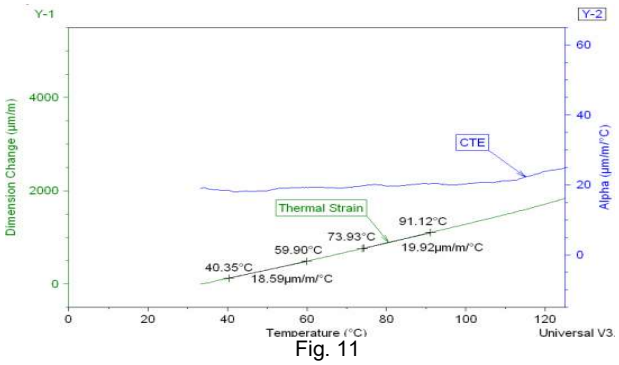

Fig. 11

Fig. 10 and Fig. 11 - Transverse thermal expansion coefficient and strain as function of temperature for $[\pm 30]_{5s}$ laminate.

4.2 Experimental verification of $[\pm 45]_{5S}$ laminate

A 45-degree template was used to cut the unidirectional prepreg, and the resulting laminate was fabricated using the autoclave method. The laminate was then tested in TMA. Since the fibers were inclined at 45 degrees to both axes, the deformation of the matrix was restricted by the fibers. As a result, the thermal expansion coefficient in the respective directions became constant.

Figure 12, the Glass Transition temperature for the longitudinal direction is shown. Figure 13, the thermal expansion coefficient at different temperatures for the longitudinal direction is shown, and the slope of the strain curve is assumed to be constant. Transverse thermal expansion coefficient and strain as function of temperature for $[\pm 45]_{5s}$ laminate

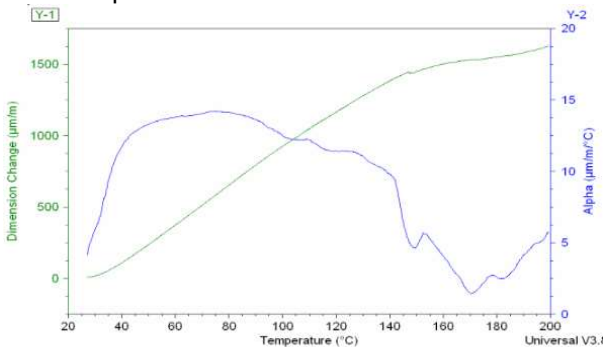

Fig. 12

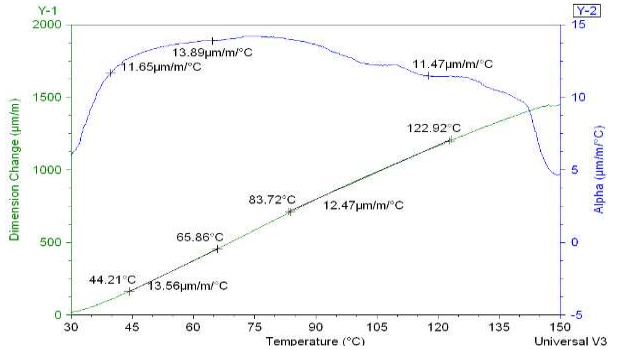

Fig. 13

Fig. 12 and Fig. 13 - Longitudinal thermal expansion coefficient and strain as function of temperature for $[\pm 45]_{5s}$ laminate.

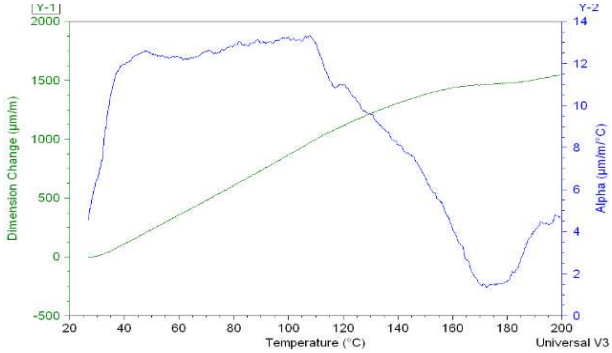

Fig. 14

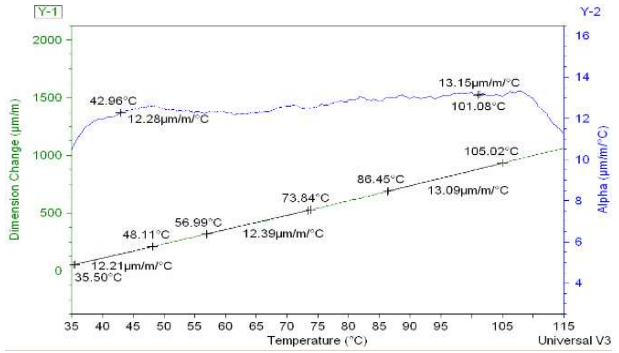

Fig. 15

Fig. 14 and Fig. 15 - Transverse thermal expansion coefficient and strain as function of temperature for $[\pm 45]_{5s}$ laminate.

Figure 14, the Glass Transition temperature for the transverse direction is shown. Figure 15, the thermal expansion coefficient at different temperatures for the transverse direction is shown, and the slope of the strain curve is assumed to be constant. which are the same as those in the longitudinal direction. Characterized Equations is given below

- α_1 = - 0.0285T+15.44
- ε_1 = 0.246T-7.2

4.3 Experimental verification of $[\pm 60]_{5s}$ laminate

A dummy template made from a metal plate was used to cut layers from a glass/epoxy unidirectional prepreg. The fibers in these layers were oriented at an angle of 60 degrees to the longitudinal direction and arranged alternately at +60 degrees and -60 degrees, resulting in a symmetric laminate with 20 layers. The laminate was fabricated using the autoclave method. Test specimens were then cut from the laminate and subjected to TMA testing to determine the thermal

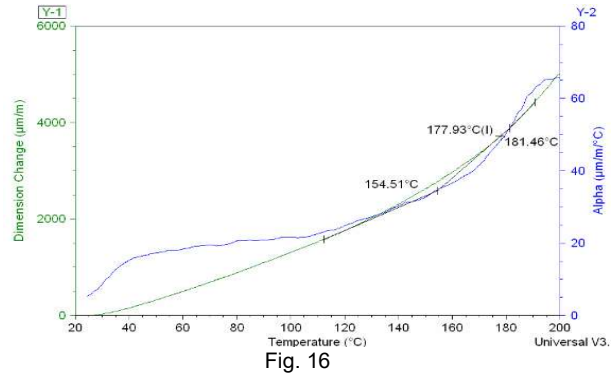

Fig. 16

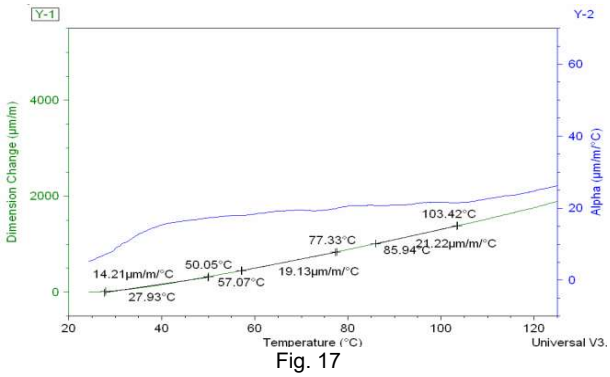

Fig. 17

Fig. 16 and Fig. 17 – Longitudinal thermal expansion coefficient and strain as function of temperature for $[\pm 60]_{5s}$ laminate.

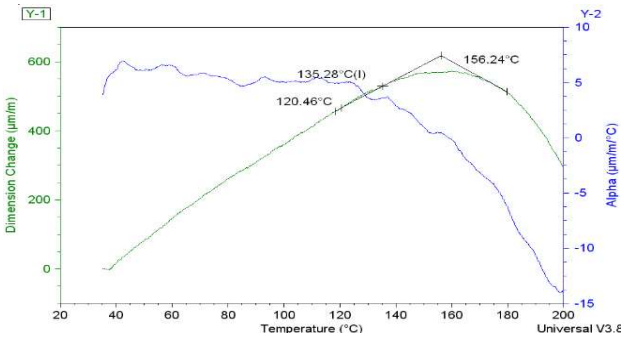

Fig. 18

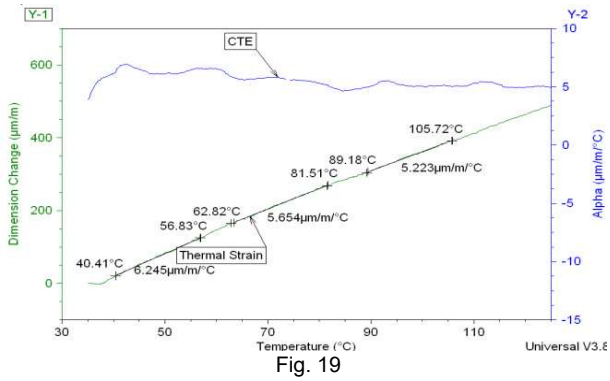

Fig. 19

Fig. 16 and Fig. 17 – Transverse thermal expansion coefficient and strain as function of temperature for $[\pm 60]_{5s}$ laminate.

expansion coefficient experimentally. Longitudinal thermal expansion coefficient and strain as function of temperature for $[\pm 60]_{5s}$ laminate.

Figure 16, The Glass Transition temperature for the longitudinal direction and the service limit curve is shown. Figure 17, Provides the thermal expansion coefficient at different temperatures in its principal direction for the longitudinal direction. Transverse thermal expansion coefficient and strain as function of temperature for $[\pm 60]_{5s}$ laminate.

Figure 18, The Glass Transition temperature for the transverse direction and the service limit curve is shown. Figure 19, Provides the thermal expansion coefficient at different temperatures in its principal direction for the transverse direction.

Characterized Equations

- $\varepsilon_1 = 0.3633T - 11.815$
- $\alpha_1 = -0.014T^2 + 0.3496T + 1.93$
- $\varepsilon_2 = 0.06T - 2.0722$
- $\alpha_2 = -0.0169T + 6.8894$

In order to verify the accuracy of analytical formulations for predicting the in-plane thermal expansion coefficient of general laminates,specimens with dimensions of 20mm x 10mm x 2.8mm were prepared. These specimens had stacking sequences of [+30]5s, [+45]5s, and [+60]5s. They were tested to measure the in-plane thermal expansion coefficient.

In Fig 20, the $[\pm 45]$5s laminate is shown, and the values of predicted and experimental thermal expansion coefficients are compared. The comparison indicates a good agreement between the predicted and experimental values. Similarly, Fig 21 and Fig 22, show the comparison between the predicted and experimental values of the $[\pm 30]$5s laminate. Fig 23 and Fig 24, display the

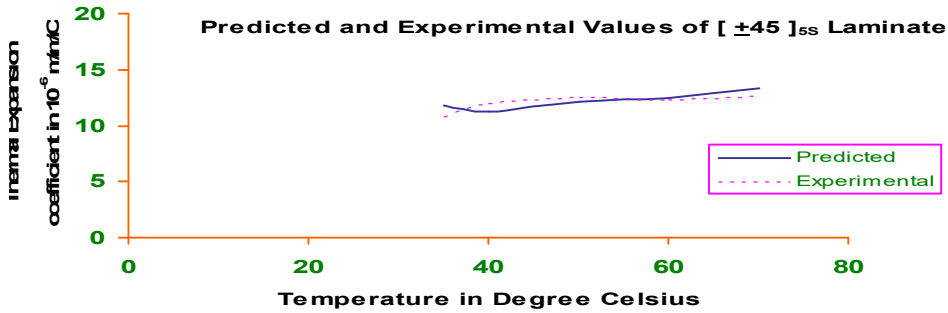

Fig. 20- Predicted and Experimental Values of [$\pm$45] Laminate

Predicted and Experimental Values of [±30] Laminate

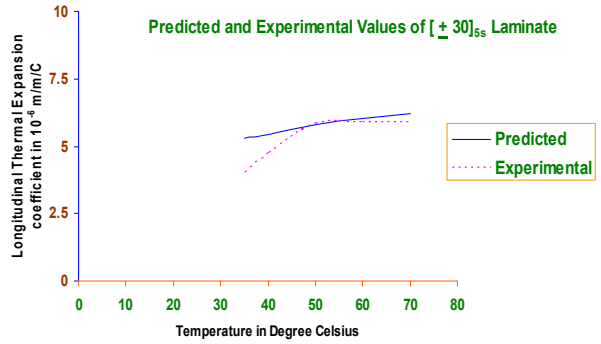

Fig. 21- Longitudinal Thermal Expansion coefficient of [±30] Laminate

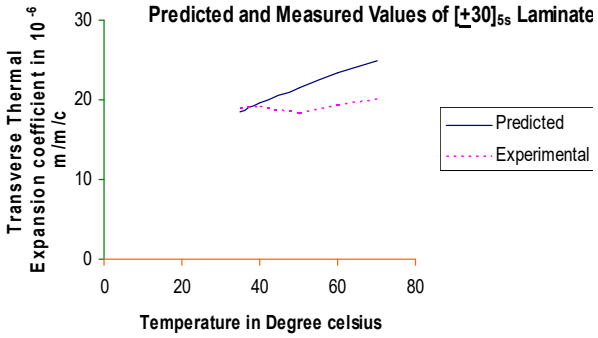

Fig. 22 - Transverse Thermal Expansion coefficient of [±30] Laminate

Predicted and Experimental Values of [± 60] Laminate

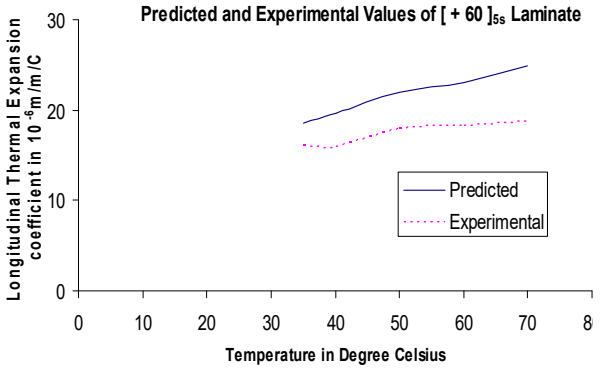

Fig. 23 - Longitudinal Thermal Expansion coefficient of [±60] Laminate

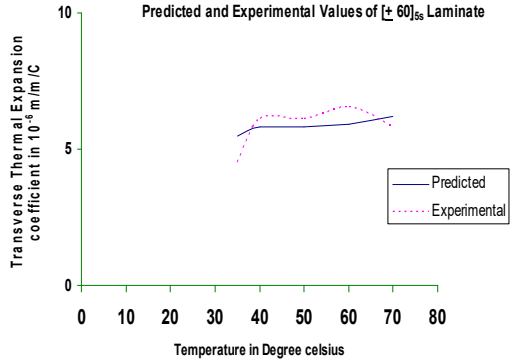

Fig. 24 - Transverse Thermal Expansion coefficient of [±60] Laminate

comparison between the predicted and experimental values of the [±60]5s laminate. These figures serve to validate the analytical formulations used for predicting the in-plane thermal expansion coefficient of laminates. The close agreement between the predicted and experimental values indicates the reliability and accuracy of the analytical approach.

5. Conclusion

Proposed analytical formulations predict changes in the thermal expansion coefficient of R-Glass/Epoxy laminates with temperature. The basic mechanical properties and thermal expansion properties of R-Glass/Epoxy laminate were measured over a range of temperatures, from room temperature to high temperature. These properties were then characterized as functions of temperature. The characterized equations of the mechanical and thermal properties were incorporated into classical Lamination theory. This allowed for the formulation of an analytic approach to calculate the change in thermal expansion coefficient. Experimental verification was conducted to validate the accuracy of the proposed formulations. The results showed that the thermal expansion coefficient of R-Glass/Epoxy laminate with various angle plies could be predicted quite well using the analytical approach.

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