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EXPERIMENTAL AND THEORETICAL STRESS ANALYSIS INVESTIGATION FOR COMPOSITE PLATE UNDER THERMAL LOAD

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ABSTRACT

A paper focuses on the investigation of the stress-strain for E-glass fiber /polyester composite plates subjected to the uniform temperature at various factors, such as fiber volume fraction and fiber orientation. To study the stress analysis of composite plate two methods are used: The First method is an experimental test by applying a uniform temperature on the composite plate inside the furnace and a measure the deformation of the plate by using dial gage. The second method based on a finite element solution using ANSYS (ver. 15) program. The results presented here that, the maximum strain in longitudinal direction occurs at a ply angle (90º), whereas the minimum value at a ply angle (0º). However, the maximum strain in transverse direction occurs at a ply angle (0º) whereas the minimum value at a ply angle (90º). In general, the magnitude of thermal strain increases with increasing temperature difference (ΔT) and decreases with increasing the fiber volume fraction (V_f).Comparison the results of the experimental test with the numerical analysis of the thermal strain and evaluated the agreement between the two methods used, the maximum discrepancy was 19.7%.

KEYWORDS: Stress Analysis, Fiber Volume Fraction, Fiber Orientation, Temperature Difference, Composite Plate

دراسة تجريبي ونظرية لتحليل صفيحة مركبة تحت الحمل الحراري

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الخلاصة

تركز هذه المقالة على التحقيق في تحليل الإجهاد لوحة مركبة من للألياف الزجاجية(E-GLASS)/البوليستر معرضة لدرجة حرارة منظمة مع تغير في الحجم واتجاه الالياف. وقد تم استخدام طريقتين لدراسة تحليل الإجهاد لوحة المركبة: الطريقة الأولى هي اختبار تجريبي بواسطة تسليط عليها درجة حرارة موحدة على لوحة المركبة داخل الفرن وقياس التشوه اللوحة باستخدام دايل كيج. اما الطريقة الثانية هي حل العنصر المحدود باستخدام برنامج ANSYS. النتائج الواردة في هذه المقالة، اعلى قيمة للانفعال في الاتجاه الطولي يحدث عندما تكون زواية الاياف (º90)، في حين ان اقل قيمة عندما تكون زواية الاياف (º0)، في حين أن اعلى قيمة للانفعال في الاتجاه العرضي يحدث عندما تكون زواية الاياف (º0) واقل قيمة عندما تكون زواية الاياف (º90). بشكل عام، فإن قيمة الانفعال الحراري تزداد مع زيادة تغير درجة حرارة (ΔT) وتنخفض مع زيادة حجم الألياف (V_f). مقارنة نتائج الاختبار التجريبي مع التحليل العددي للانفعال الحراري وتقييم الاتفاق بين الطريقتين المستخدمة، واعلى نسبة خطأ هي 19.7٪.

1. INTRODUCTION

Fiber-reinforced polymer (FRP) is a composite material formed of a polymer matrix reinforced with fibers. The polymer is commonly a vinyl ester or polyester thermosetting, and an epoxy, and. The fibers are commonly carbon, glass, etc. Applications for the same are in aerospace industry, sporting goods industry, automotive industry, and home appliance industry (Patel, et al, 2014). With the increased use of composite materials in thermal environments, the temperature effect on the fiber-matrix interface is as strong as those of the fiber treatment and resin properties (Matsunaga, 2004); an adequate knowledge of the deflections and stresses induced by thermal loads in these structures is of prime interest for structural analysts. The excessive stress levels caused by temperature are, in fact, often the predominant cause of failure of laminated composite structures (Robaldo, et al, 2005).

The analysis stresses and deflections in composite laminated plates (The boundary conditions considered for the analysis are simply supported and clamped supported) due to thermal loads, the formulation based on first order shear deformation theory has been employed for the analysis. The effects of different parameters, such as ply-angle, a number of layers, thickness and aspect ratios on stresses and deflections are brought out, presented by Ganapathi, et al. (1996).

Aloisi, et.al, (1998) used strain gauges for the measurement of internal deformation in the laminated composite material the methodology consists in inserting the strain gauges among the layers of the laminate before polymerization in the oven. The results obtained showed good agreement with theoretical values from simple calculations.

In 2005 Drukker et al., studied the effects of the development of thermal stresses due to exposure to three-dimensional (3D) temperature gradients where temperature differences may exceed 150 ºC in a glass fabric-reinforced Polyimide resin laminate.

And Dharma Raju and Suresh Kumar in 2011, investigated the thermal characteristics of laminated composite plates based on higher-order displacement model with zig-zag function under thermal loading by developed an analytical procedure.

Also in 2013 Swaminathan and Fernandes, Analytical formulations and solutions based on higher order refined theory for the stress analysis of simply supported cross-ply laminated composite plates subjected to thermal load were presented.

Finally, in 2014 Kulikov and Plotnikova, focused on the application of the method of sampling surfaces (SaS) to three-dimensional (3D) steady-state thermo elasticity problems for orthotropic and anisotropic laminated plates subjected to thermal loading.

The practical application for research in areas where a change in temperature occurs, such as the fan or propeller used to cool the system and operate at variable temperature. In this work, the composite plate that was affected by thermal strain due to temperature variation was analysied. An experimental work was compared with the numerical study of thermal strain for a composite plate (E-glass/polyester) subjected to the uniform temperature. In addition to studying the effect of two factors, fiber volume fraction and fiber orientation.

2. THEORETICAL ANALYSIS

2.1. Mathematical models

Analysis of mechanical stress of reinforced lamina at the temperature higher than the operating temperature should be complemented by the analysis of thermal stresses.

The relation of linear stress-strain for layer is expressed with x, y-axes and has the form, (Hartwig, 1988) and (Shinde, et al., 2013).

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{61} & \bar{Q}_{62} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x - \alpha_x \Delta T \\ \varepsilon_y - \alpha_y \Delta T \\ \gamma_{xy} - \alpha_{xy} \Delta T \end{bmatrix} \qquad 1$$

Where, σ_x, σ_y, and τ_{xy} are components of the stress, $\bar{Q}_{ij}$ are the transformed reduced stiffness's, which can be expressed in terms of the orientation angle and the engineering constant of the material, ΔT is the temperature increase, α_x and α_y are the coefficients of thermal expansion in direction of x and y-axes respectively. α_{xy} is the apparent coefficient of thermal shear such as

$$\alpha_x = \alpha_1 cos^2\theta + \alpha_2 sin^2\theta$$
$$\alpha_y = \alpha_2 cos^2\theta + \alpha_1 sin^2\theta \qquad 2$$
$$\alpha_x = 2(\alpha_1 - \alpha_2) \sin\theta \cos\theta$$

Where, α_1 and α_2 are the coefficient of thermal expansion for the lamina along the longitudinal and transverse direction of fibers, respectively. The resultant forces N_x, N_y and N_{xy} are given as

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz \qquad 3$$

And, the moments M_x, M_y and M_{xy}, per unit length of the plate are given as

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} zdz \quad 4$$

Where, h is the total thickness of lamina.

2.2. Governing equation of plate

Based on the fundamental of minimum total potential energy (π) can be derived the governing equation of a composite plate

$$\pi = U - W \quad 5$$

Strain energy of the plate is expressed as

$$U = \frac{1}{2} \int \{\sigma\}\,\{\epsilon\}\, dV \quad 6$$

And work done by external load

$$W = \iint \{u\}^T \{q\} dA \quad 7$$

Where, V represent plate volume and A plate area and {q} are uniformly distribution loads per unit area along x and y-axes respectively. To minimize the total potential energy of the plate with respect to its deformation, the plate has to satisfy

$$\frac{\partial \pi}{\partial \delta} = 0 \quad 8$$

Using Eqn. (6) and (7) we get from Eq. 5

$$[K]^e * \{\delta\}^e = \{Q\}^e \quad 9$$

The stiffness matrix

$$[K]^e = \iint [B]^T [D][B] dxdy \quad 10$$

And the generalized force matrix

$$\{Q\}^e = \iint [N]^T \{q\} dxdy \quad 11$$

Where, $\{\delta\}$ - the displacement vector, [B] -the interpolation matrix. (B. N. Pandya & T. Kant, 1988)

2.3. Mechanical and thermal properties of composite material

Rule mixture is the simplest method to determine the elastic properties for a unidirectional composite material, based on the characteristics of each of the constituents the elastic properties can be obtained for the fiber/matrix mixture. The longitudinal modulus E_1 can be estimated by (Gay, et al, 2003)

$$E_1 = E_f . V_f + E_m . (1 - V_f) \qquad 12$$

The transverse modulus E_2 and shear modulus G_{12} are given as:

$$E_2 = \frac{E_f E_m}{E_f \mathrm{v}_m + E_m \mathrm{v}_f} = \frac{E_f E_m}{E_f \mathrm{v}_m - \mathrm{v}_f (E_f - E_m)} \qquad 13$$

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f} \qquad 14$$

Other rules of mixture expressions for lamina properties include those for major and minor Poisson's ratio

$$\upsilon_{12} = \upsilon_f \mathrm{v}_f + \upsilon_m \mathrm{v}_m \qquad 15$$

$$\upsilon_{21} = \frac{E_2}{E_1} \upsilon_{12} \qquad 16$$

Mass density of the unidirectional continuous fiber composite can be calculated as

$$\rho_c = \rho_f V_f + \rho_m V_m \qquad 17$$

For a unidirectional continuous fiber lamina, the linear thermal expansion coefficients can be calculated as

$$\alpha_{11} = \frac{\alpha_{fl} E_f \mathrm{v}_f + \alpha_m E_m \mathrm{v}_m}{E_f \mathrm{v}_f + E_m \mathrm{v}_m} \qquad 18$$

And

$$\alpha_{22} = (1 + \upsilon_f) \frac{(\alpha_{fl} + \alpha_{fr})}{2} + (1 + \upsilon_m) \alpha_m \mathrm{v}_m - \alpha_{11} \upsilon_{12} \qquad 19$$

Where, m and f indicate to matrix and fiber properties respectively,α_{fl}, and α_{fr} represent the linear thermal expansion coefficient for the fiber in the longitudinal and the radial direction respectively.

3. PROBLEM DESCRIPTION

In this paper, the thermal strain is determined for three sides of the composite plate are free and one side is clamped. The plates subjected to uniformly distributed temperature difference, (30ºC and 60ºC) the dimensions of the composite plate can show in Fig. 1 and the properties of material are shown in Table.1 (Daniel and lshai, 2006).

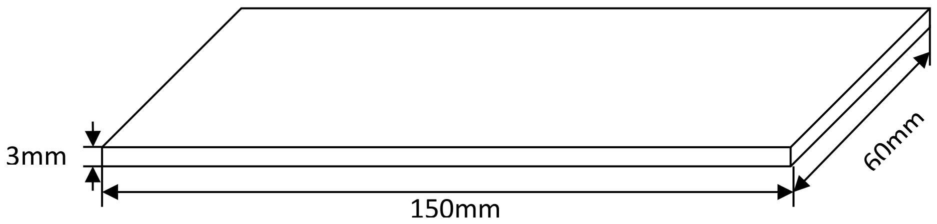

Fig. 1. Geometry and dimensions of the composite plate.

Table. 1. The material properties of (E-glass\polyester) plate (Daniel and lshai, 2006).

Material property	**Fiber material (E-glass)**	**Matrix material (polyester)**
Young's modulus, GPa	73	3.2
Poisson’s ratio	0.23	0.35
Shear modulus, GPa	29.67	1.185
Coefficient of thermal expansion, 10^{-6}/ºC	5	60
Density g/cm³	2.54	1.1

4. FINITE ELEMENT MODEL

The finite element method (FEM) is a numerical tool for determining solutions to large class of engineering problems, ANSYS software package has been used to analyses composite plate. For modeling the composite plate, the SHELL181 element is used. Shell181 is proper for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions as shown in Fig. 2, and rotations about the x, y, and z-axes. It is suitable for linear, large rotation, and/or large strain nonlinear applications. It accounts for follower (load stiffness) effects of distributed pressures. It can be also utilized for layered applications for modeling composite shells or sandwich structure. The accuracy in modeling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reisner shell theory) (Singh and Pal, 2016).

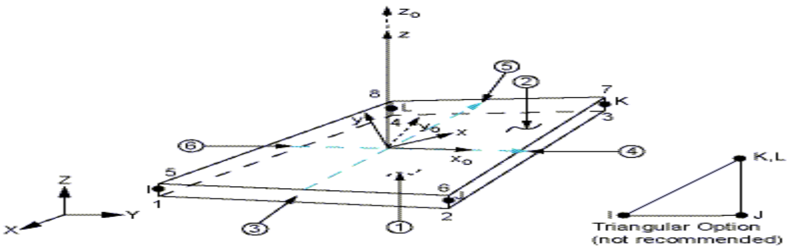

Fig. 2. Shell 181 geometry.

5. EXPERIMENTAL WORK

The materials used to manufacturing the samples are glass fibers long reinforcement fiber and polyester as a resin matrix. The weight of each fiber and resin depended on the volume fraction of fiber and resin, and can be calculated from the following expressions (Jweeg, et al, 2012).

$$wightoffiber = \rho_c V_t V_f \tag{20}$$

$$wightofresin = \rho_c V_t V_m \tag{21}$$

Rectangular E-glass/polyester composite specimens were fabricated by using volume fraction of fiber ($V_f = 5\%$) the hand lay-up technique used to manufacturing the composite plate. The most basic fabrication method for thermoset composites is hand lay-up, which typically consists of laying dry fabric layers or plies by hand onto a tool to form a laminate plate. The polymer type that used It is determined the time of curing for composite processing normal curing time at room temperature is (24-48) hours. The high-value fraction of reinforcement is difficult to achieve the processed composites. The specimens were cut for testing by brick cutting machine into 160*60 mm, the thickness of lamina was measured as 3 mm as shown in Fig. 3.

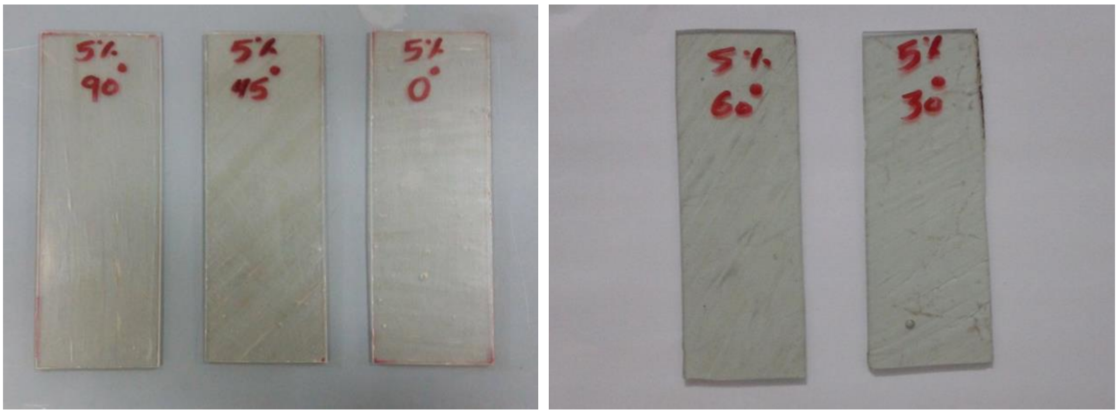

Fig. 3. Samples of composite plate.

6. TEST MACHINE

A device that will be used to exam the deformation of the samples is shown in the Figs. 4 and 5, the test components include the following parts:

1. Structure to support the test machine.
2. Electric oven size 200*250*300mm and the highest temperature arrive 250 ° C has been altered from the top for the installation of detent which will hold the sample in order to achieve clamped boundary condition, either three sides remaining been drilled to pass through which tube conduction (tube Pyrex) to connect between the aspects of the sample with measuring deformation device (dial gage)
3. Dial gage, it is a device used for measuring deformation, measuring range (12.7 mm), resolution (0.01), and accuracy (20μm).
4. Tube Pyrex, it is used to connect between the sample in the furnace and deformation measuring device outside the furnace.

The dial gage measured the deformation of a composite plate in the longitudinal and transverse direction (δ_x, δ_y).The reading of dial gage has been marked, and the values of deformation turned into strain by using this law

$$\varepsilon = \frac{\delta}{l} \qquad 22$$

Where, δ represent the change in length and l represent an original length of the plate.

And then are subtracted strain values for Pyrex tubes because the temperature of final strain values, strain of Pyrex tubes is calculated from the law of thermal strain

$$\varepsilon_{thp} = \alpha_p \Delta T \qquad 23$$

Where, α_p represent the coefficient of thermal expansion for Pyrex equal $3.3 * 10^{-6}$/ºC (Cheng-Chung, et al., 2001) and ΔT represent temperature difference.

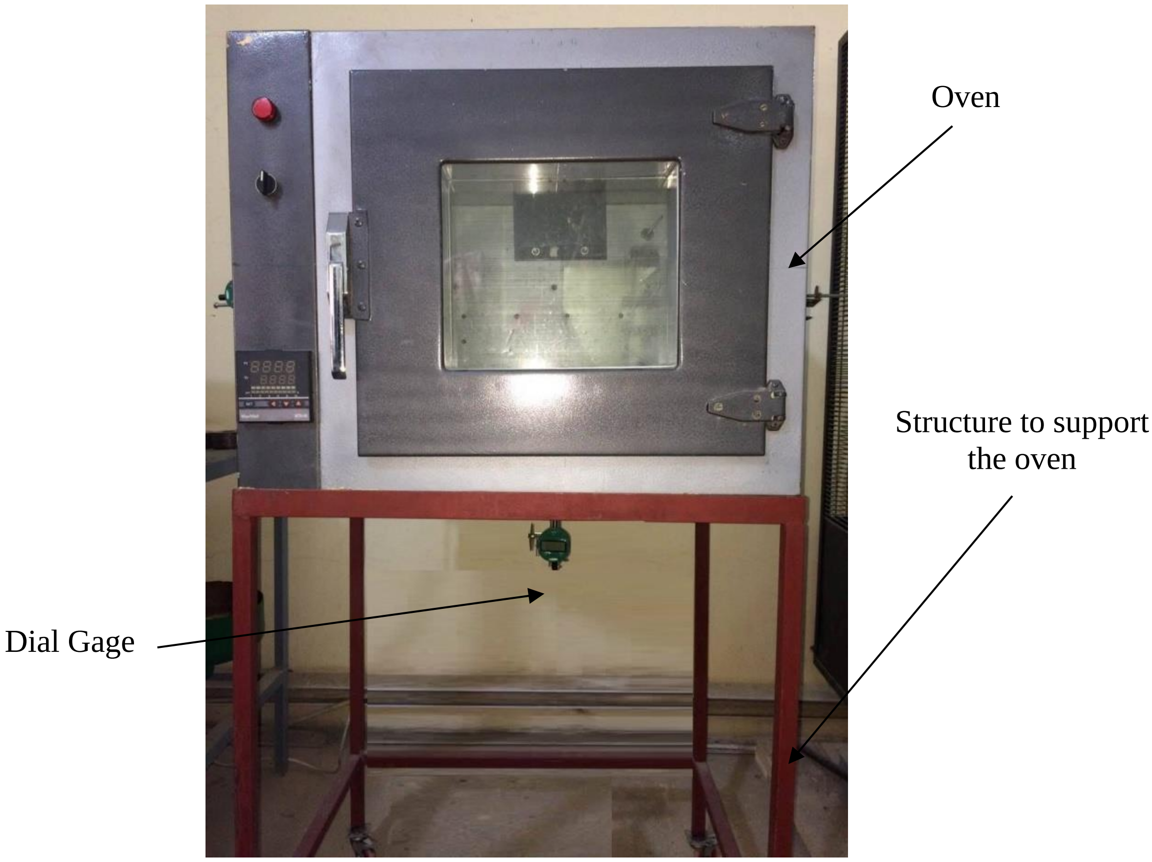

Fig. 4. Test Machine.

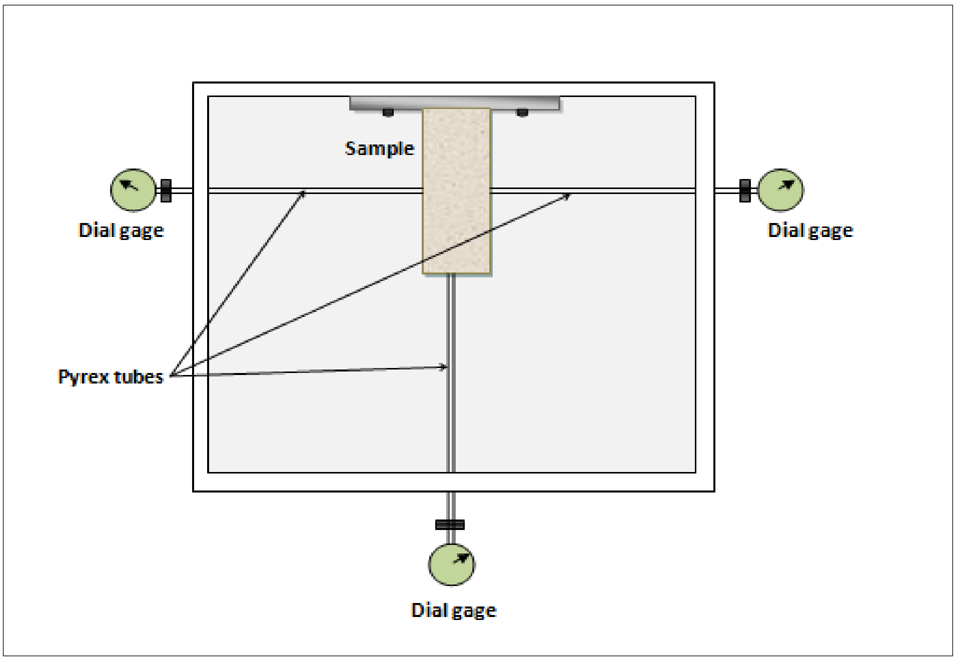

Fig. 5. Scheme shows the installation of the sample and Pyrex tubes inside the oven.

7. RESULT AND DISCUSSION

In this section, the responses of an orthotropic composite plate under the effect of uniform temperatures difference have been performed using ANSYS software and experimental test. The same temperature will be exposed on all region of plate structure, selected uniformly for the thermal loading, it was applied with different values of that chosen temperatures, like (30°C, 60°C). The results were showed in Figs. 6, 7, 8 and 9 depending on applied temperature, fiber orientation and fiber volume fraction.

Firstly, in these figures it is seen the strain values in longitudinal and transverse direction decreases with increasing fiber volume fraction, due to increases the strength and modulus of elasticity as the fiber volume fraction increasing.

Other important point in these figures it observed that, the strain value in longitudinal direction increased with increasing fiber orientations, whereas, the strain transverse direction decreased with fiber orientations increasing.

Additionally, another significant point in these figures, the magnitude of thermal strain is increased with increasing of constant temperature values, therefore the maximum absolute of thermal strain occurred at 60°C constant temperature loading, while the minimum absolute values of it are obtained at 30°C constant temperature loading. Because, the matrix properties are sensitive to change in temperature. Therefore, composite properties which are strongly influenced by matrix properties this case is also true for all selected lamina orientations.

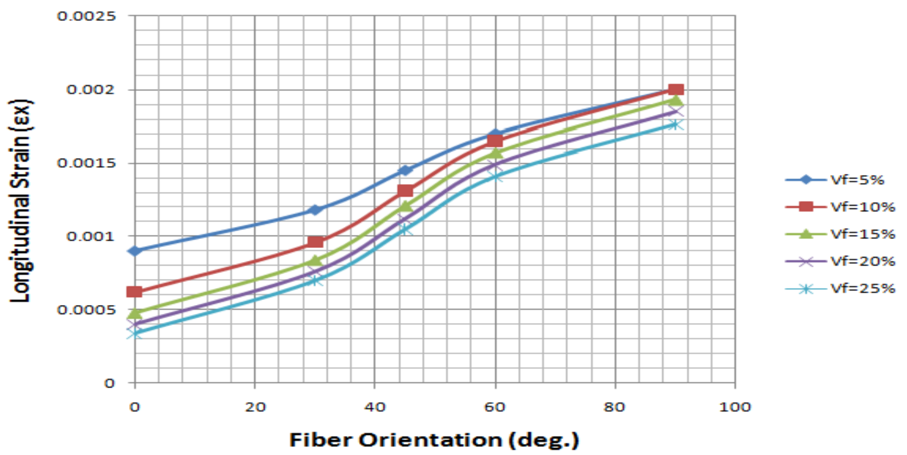

Fig. 6. Longitudinal thermal strain with fiber orientation at variousvolume fraction, ($\Delta T = 30^{o}C$).

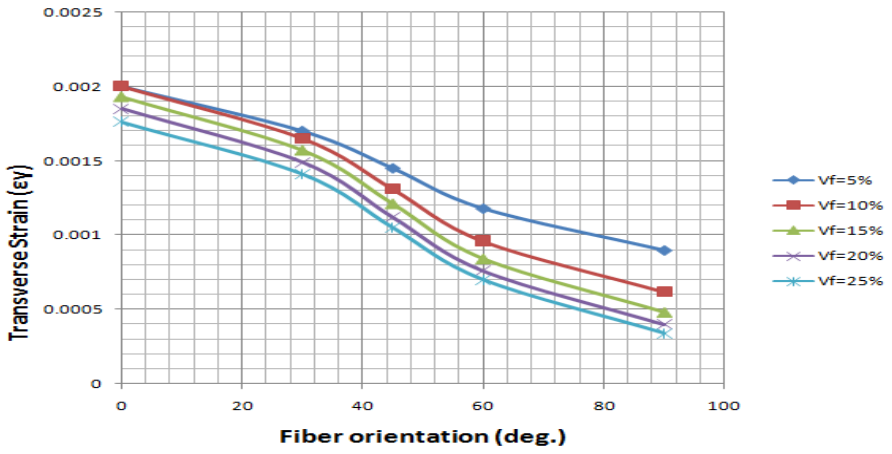

Fig. 7. Transverse thermal strain with fiber orientation at variousvolume fraction, ($\Delta T = 30°C$).

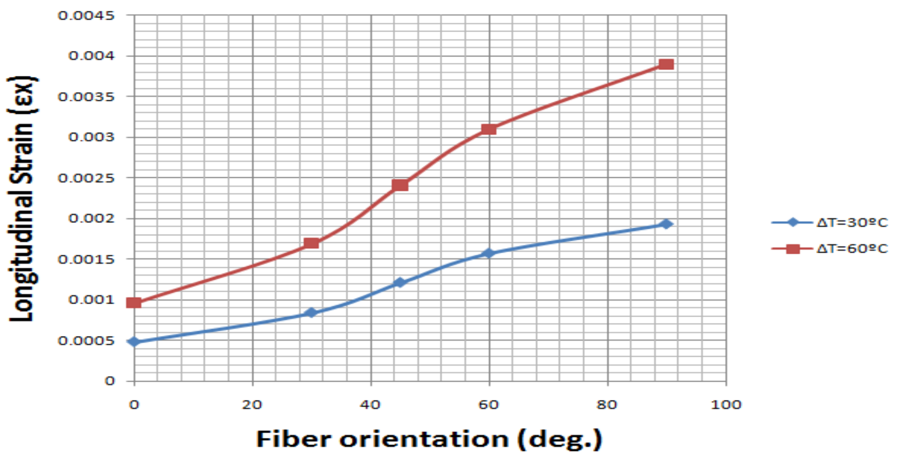

Fig. 8. Represent strain values in longitudinal obtained numerically at ($\Delta T = 30°C, \Delta T = 60°C, V_f = 15\%$)

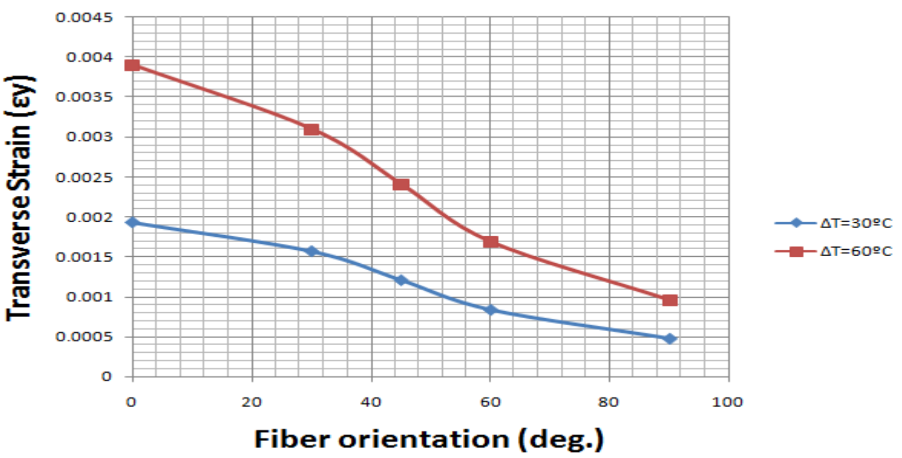

Fig. 9. Represent strain values in transverse obtained numerically at ($\Delta T = 30°C, \Delta T = 60°C, V_f = 15\%$)

The experimental result for the orthotropic composite plate at fiber volume fraction 5% is compared with numerical analysis using Ansys program. As shown in Figs. 10, 11, 12, 13, 14, 15.

It is found to be reasonable in good agreement with numerical result. The percentage of the discrepancy is about 19.7%.

So, it can be said clearly that, the magnitude of thermal strain increases with increasing temperature different and decreases with increasing the fiber volume fraction, the thermal stress cause the change in dimension of the structure and it needs to have the consideration is given to design process.

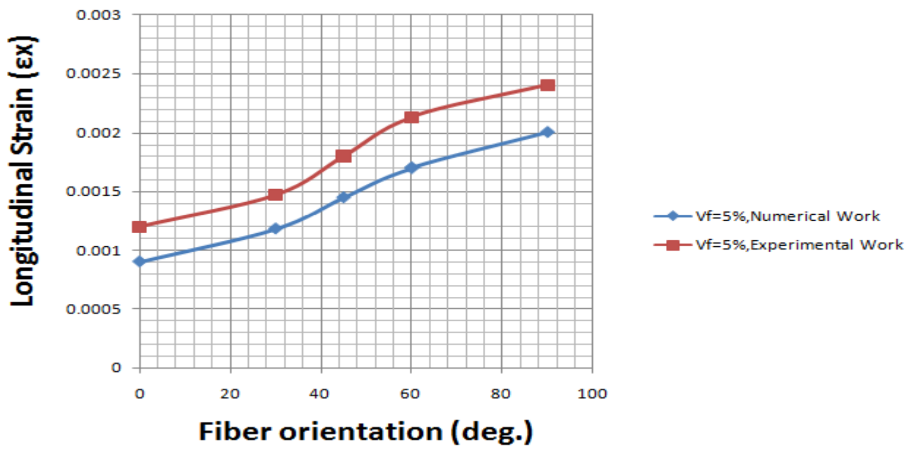

Fig. 10. Comparison of longitudinal strain for composite plate at$\Delta T = 30^{o}C$.

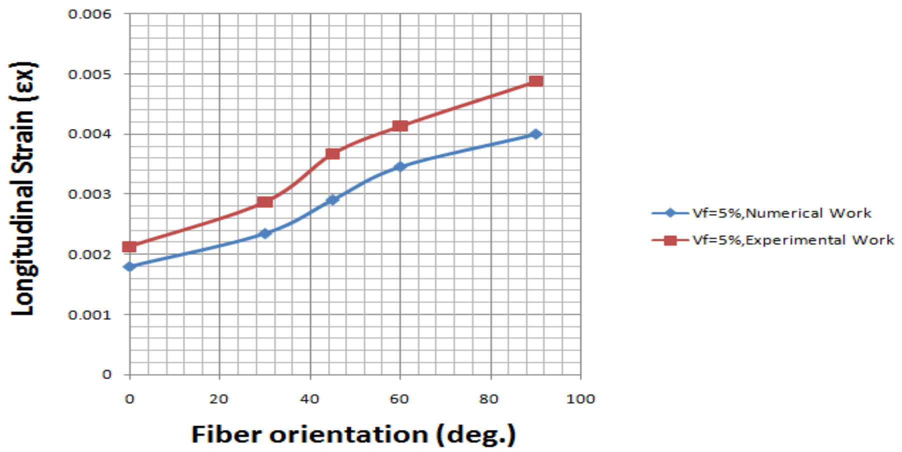

Fig. 11. Comparison of longitudinal strain for composite plate at $\Delta T = 60^{o}C$.

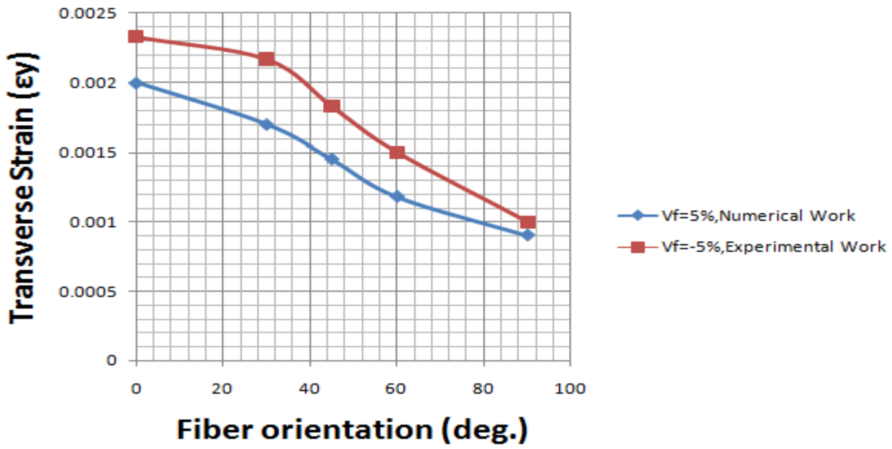

Fig. 12 Comparison of transverse strain for composite plate at $\Delta T = 30^{\circ}C$.

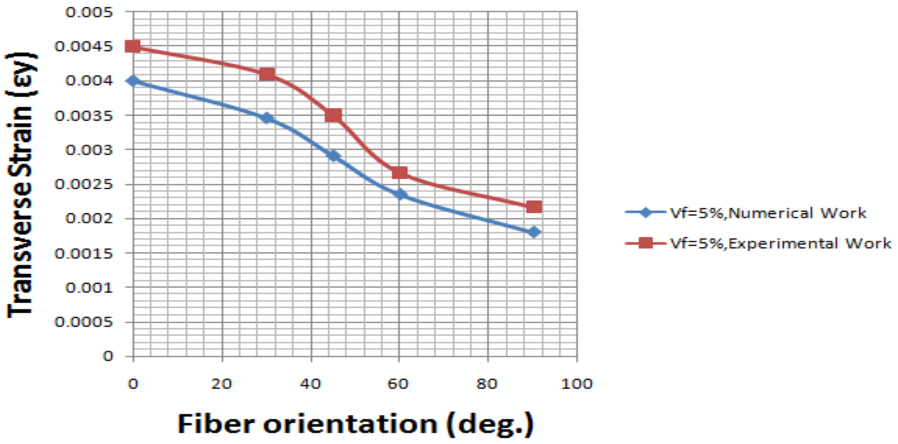

Fig. 13. Comparison of transverse strain for composite plate at $\Delta T = 30^{\circ}C$.

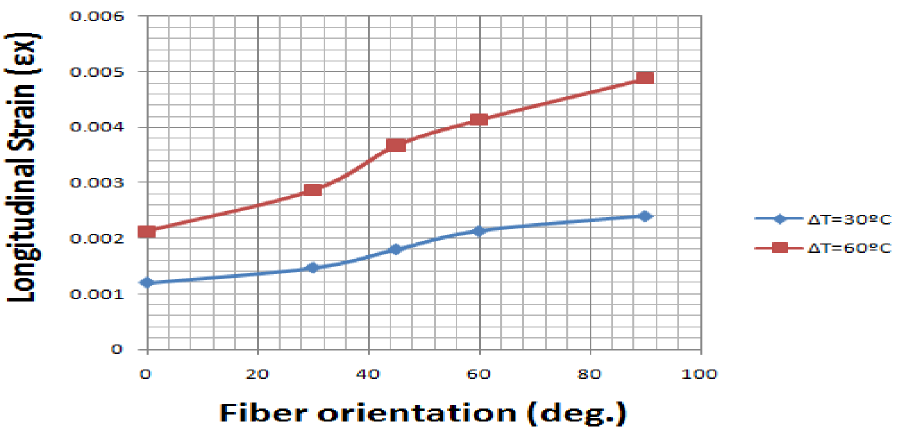

Fig. 14. Represent strain values in longitudinal obtained experimental at ($\Delta T = 30^{\circ}C, \Delta T = 60^{\circ}C$).

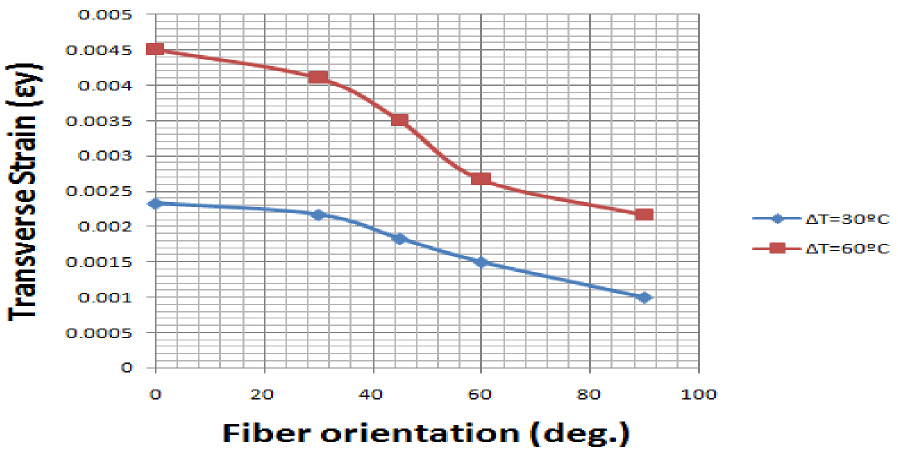

Fig. 15. Represent strain values in transverse obtained experimental at ($\Delta T = 30^{o}C, \Delta T = 60^{o}C$).

8. CONCLUSIONS

The following conclusions can be draw from the above analysis:

1. Thermal strain in longitudinal and transverse direction increases with increasing temperature different, and decreases with increasing the fiber volume fraction.
2. The maximum strain in longitudinal direction occurs at a ply angle (90º) for E-glass \polyester plate and the minimum value at a ply angle (0º). As the fiber orientation increases, the strains in longitudinal direction also increasing.
3. The minimum strain in transverse direction occurs at a ply angle (90º) for E-glass \polyester plate and the maximum value at a ply angle (0º). As the fiber orientation increases, the strains in transverse direction also decreasing.
4. The results conclude that numerical and experimental values are convenient which provides the permission to use numerical strain analysis for the composite material, the maximum percent error about 19.7%.

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