Experimental And Theoretical Stress Analysis For Composite Plate Under Combined Load

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Abstract

The combined effects of thermal and mechanical loadings on the distribution of stress-strain for E-glass fiber /polyester composite plates are investigated experimentally and numerically. The experimental work has been carried out by applying to a uniform temperature and tensile load on the composite plate inside the furnace and the deformation of plate measured by a dial gauge. Two parameter studies, the fiber volume fraction and fiber orientation on the stress-strain for plates subjected to identical mechanical and temperature gradient. The results presented showed that, the maximum absolute of total strain in longitudinal direction occurred at 50 N tension load and fiber angle 60º, while the minimum absolute values of it occurred at 15 N tension loads and fiber angle 0º. However the maximum absolute of total strain in transverse direction occurred at 15N tension load and fiber angle 0º, while the minimum absolute values of it are obtained at 50 N tension loads and fiber angle 60º. Also, the total strain in longitudinal and transverse direction decrease with increasing the fiber volume fraction. Comparison of the results in the experimental test with the numerical analysis of the total strain and evaluated the agreement between the two methods used, the maximum discrepancywas 20%.

Keywords: Fiber Volume Fraction, Fiber Orientation, Temperature Difference, Composite Plate, Tension load.

الخلاصه

تم دراسة التأثير المشترك للحمل الحراري والميكانيكي على توزيع إجهاد–الإنفعال لصفيحة من الياف الزجاج والبوليستر المركبة بطريقتين التجريبيه والعدديه .العمل التجريبي تم من خلال تسليط درجة حرارة منظمة و حمل شد على الصفيحة مركبة داخل الفرن وقياس تشوه اللوحة باستخدام dial gage مع دراسة تأثير أثنين من العوامل ، حجم الألياف وأتجاه الألياف على تحليل الاجهاد – الانفعال مع مماثلة الميكانيكية والحرارية التحميل .النتائج المعروضة هنا أن الحد الأقصى المطلق للإنفعال الكلي في الاتجاه الطولي حدث عند قوة شد 50 نيوتن وزاوية الألياف 60º، في حين أن القيم المطلقة الدنيا منه حدثت عند قوة شد 15 نيوتن وزاوية الألياف 0 .ºومع ذلك، فإن الحد الأقصى المطلق للإنفعال الكلي في الاتجاه العرضي حدث عند قوة شد 15نيوتن وزاوية الألياف 0º، بينما تم الحصول على القيم المطلقة الدنيا عند قوة شد 50 نيوتن وزاوية الألياف 60 .ºوأيضا، فإن إنفعال الكلي في الاتجاه الطولي والعرضي ينخفض مع زيادة حجم الألياف. تم مقارنة نتائج الاختبار التجريبي مع التحليل العددي للإنفعال الكلي وتقييم الاتفاق بين الطريقتين المستخدمتين، الحد الأقصى من التناقض 20٪.

الكلمات المفتاحية: حجم الألياف ، اتجاه الألياف، الفرق في درجة الحرارة، الصفيحة المركبة، قوة الشد.

1- Introduction

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. **(Campbell, 2010)**. The useful alternatives to metals and alloys are Reinforced polymer composites (RPC) when it requires to high strength, low weight and low cost. These materials are found to be surprisingly dependable for use in fire hazard areas In spite of their combustibility and their quick loss of structural integrity. the composite material when loaded mechanically and heated to high temperatures the behavior of it become complex.

The reinforced polymer composites, and in particular, glass reinforced plastic (GRP) are among the new materials increasingly being used in the offshore industry. Their current applications range from topside such as primary structures, blast and corrosion protection, aqueous pipe work, tanks, vessels and firewater systems to subsea such as instrument housing, emergency shutdown valve and riser protections where extreme conditions such as high pressures, high temperatures, mechanical impact and corrosion or a combination of all are involved. Glass reinforced plastic ideal for a wider range of applications compared with steel and aluminum, this is because there desirable properties such as high specific strength (proof strength/specific gravity) and specific stiffness (Young's modulus/specific gravity). Two parameters limit their use: the first is fire, smoke, toxicity and the service temperature, and, the second is their load-bearing capability under extreme conditions **(Looyeh *et.al.*, 2005).** An adequate knowledge of the deflections and stresses induced by thermal and mechanical loads is very important for structural analysts. Actually, Often the dominant reason for the failure of composite laminated structures is the excessive stress levels caused by temperature and tension.

Performed a numerical and analytical to study the thermal stresses on composite plate is subjected to combine thermal and mechanical loading with simply supported boundary conditions. The materials used in this work are graphite fiber and epoxy resin. The composite plate is manufactured on (0º/90º/0º) orientation. **(Tungikar and Rao**,**1994**)

(Ali *et.al.*, 1999) formulated a new displacement –based higher-order theory. The theory employs realistic displacement variations and is shown to be accurate for even thick laminates and for any combination of mechanical and thermal loading.

(In 2005 Vnučec), performed the numerical analysis to predict the engineering properties of the multilayered plate and described the stress-strain distributions for various lamination angles of continuous fiber composite laminate. The materials used for reinforcement are E-glass fibers, and the matrix material was the epoxy resin. The computations of the stress and strain values for the angle-ply four-layered symmetric laminated plate with various lamination angles of laminas under combined loads are carried out.

(JIN *et.al.*, 2008) determine the micro stress within a unidirectional composite under various mechanical and thermal loading conditions. Based on linear stress–strain relations, three unit cell models, square, hexagonal, and diamond fiber arrays, are analyzed and compared using three-dimensional finite element methods.

(choudhury *et.al.*, 2017) performed Analytical formulation to study the stress analysis of composite plate under the effect of thermo mechanical loading for different ply orientation and thickness of lamina. The materials used are fiber glass and epoxy resin and the orientation of the layers is assumed to be antisymmetric about the neutral axis of the laminate.

The practical application for research in areas where a change in temperature with load occurs, such as the fan or propeller used to cool the system and operate at temperature variations. In this work, an analysis to the composite plate that is affected by total strain due to temperature and tension load variations has been conducted numerically and experimentally. An experimental work is done to measure the total strain in longitudinal and transverse direction.

2. Mathematical models

The lamina consists of orthotropic materials. The thickness of ply is constant, and the ply has arbitrary angles relative to the x- axis. In most structural applications, composite materials are used in the form of thin laminates loaded in the plane of the laminate. The relation of linear stress-strain for layer is expressed with reference axes has the form**,(Hartwig, 1988; Shinde *et.al.*, 2013)**

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

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 variation, 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

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

Where, α_1 and α_2 are the coefficient of thermal expansion for the lamina along the principal direction of fibers. 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

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

Where, h is the total thickness of lamina.

3. Governing equation of plate

Based on the fundamental of minimum total potential energy (π) can be derived the governing equation of a composite plate is **(Pandya and Kant, 1988)**

$$\pi = U - W \qquad (5)$$

Strain energy of the plate is expressed as

$$U = \frac{1}{2}\int\{\sigma\}\{\epsilon\}\, dV \qquad (6)$$

And work done by external load

$$W = \iint\{u\}^T\{q\}dA \qquad (7)$$

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

$$\frac{\partial\pi}{\partial\delta} = 0 \qquad (8)$$

Using Eqns. (6) and (7) with Eqn.(5) to get

$$[K]^e * \{\delta\}^e = \{Q\}^e \qquad (9)$$

The element stiffness matrix can be written as

$$[K]^e = \iint[B]^T[D][B]dxdy \qquad (10)$$

And the generalized force matrix

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

Where, $\{\delta\}$ - the displacement vector, [B] – element strain displacement matrix, $[D]$ – material matrix, $[N]$ – the shape function matrix. **(Pandya and Kant, 1988)**

4. Mechanical and thermal properties of composite material

The 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)**

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

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

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

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f} \quad (14)$$

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

$$\upsilon_{12} = \upsilon_f \mathrm{v}_f + \upsilon_m \mathrm{v}_m \quad (15)$$

$$\upsilon_{21} = \frac{E_2}{E_1} \upsilon_{12} \quad (16)$$

Density of the unidirectional continuous fiber composite can be calculated as

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (17)$$

For a unidirectional continuous fiber lamina, the linear thermal expansion coefficients can be calculated as **(Gay *et.al.*, 2003).**

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

And

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

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.

5. Problem Description

In this paper, the total strain is determined by a composite of plate three sides plate which are free and one side is clamped. The plate is subjected to uniformly distributed temperature variation and tension load, the dimensions of the composite plate can be illustrated in Figuer1 and the properties of material are shown in Table.1 **(Daniel and lshai, 2006)**

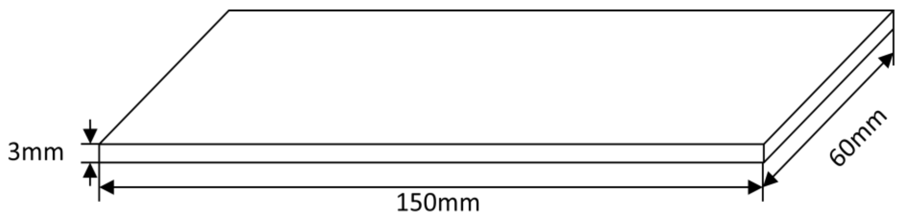


Fig. 1 Geometry and dimensions of the composite plate

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 Figure2, 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).**

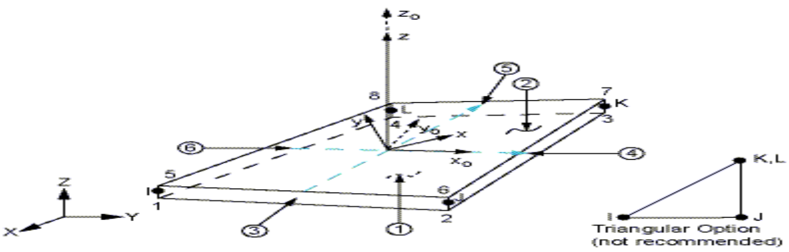


Fig. 2 Shell 181geometry

5. Experimental Work

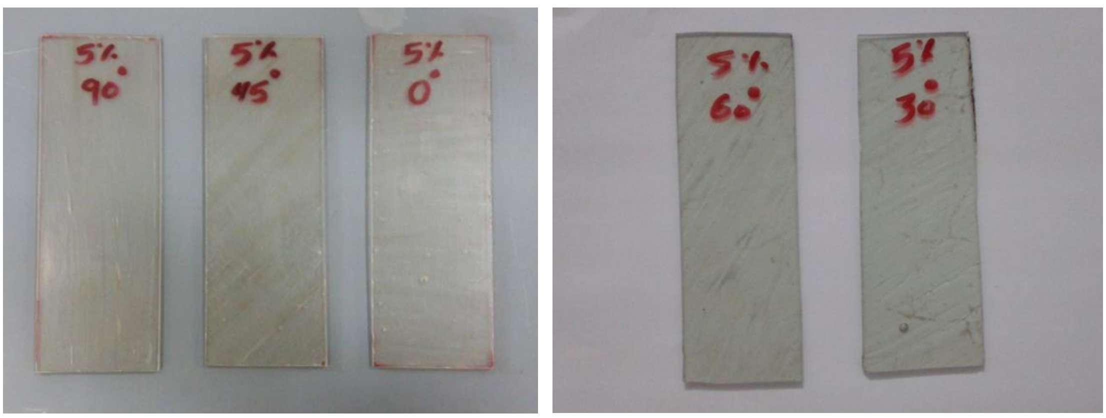
The materials used to manufacture the samples are glass fibers with long reinforcement fiber and polyester as a resin matrix**.** The weight of each fiber and resin depended on the volume fraction of fiber and resin and can be calculated from the following expressions **(Jweeg *et.al.*, 2012)**,

$$wightoffiber = \rho_c V_t V_f \quad (20)$$

$$wightofresin = \rho_c V_t V_m \quad (21)$$

Rectangular E-glass/polyester composite specimens were fabricated by using fiber volume fraction (5%). The hand lay-up technique used in manufacture 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 curing time for composite material is (24-48) hours. The specimens were cut for testing by brick cutting machine into 160*60 mm, the thickness of lamina was measured as 3 mm the samples of composite plate as shown in Figure 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 Figures 4 and 5, the test components include the following parts:

1- Structure to support the test machine.

2- Electric oven size 200*250*300mm with maximum of 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; the other sides have been drilled to allow for passing of tube (tube Pyrex) to connect the aspects of the sample with the 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- Pyrex Tube, it is used to connect the sample in the furnace and the dial gauge.

5-Install parts of load, the sample bearing by required weights in an indirect way, by installing the free end of the sample using two thick plates (connecting them with screws) which in turn connects with the two wires of aluminum, it ends with a thick plate hanging by hook.

The dial gage was 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

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

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

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

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

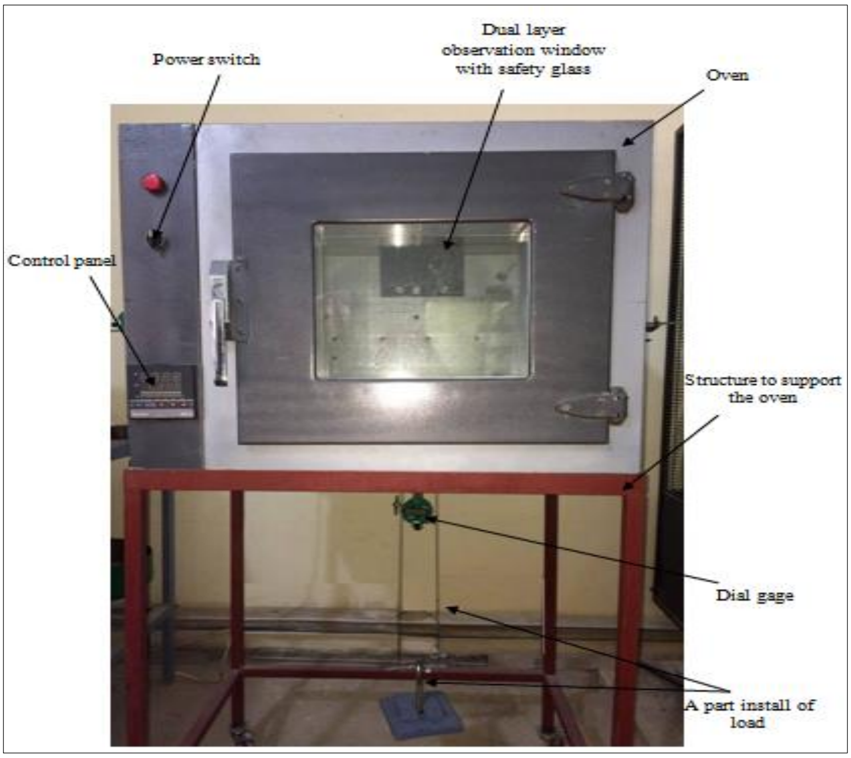


Fig.(4) Test Machine

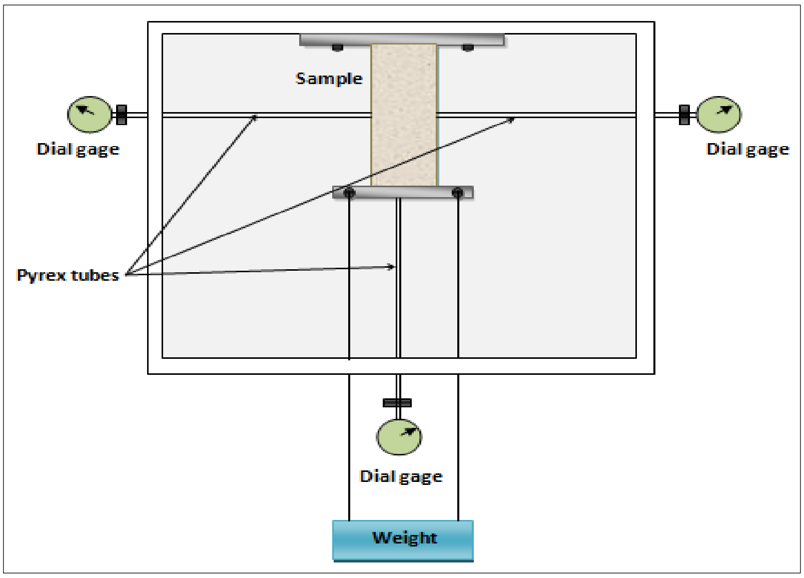


Fig.(5) Scheme shows the installation of the sample, Pyrex tubes and load inside the oven

7. Result And Discussion

The responses of an orthotropic composite plate under the effect of uniform temperatures difference and tensile load have been performed using ANSYS software and experimental test. The same temperature and tensile load will be exposed on all region of plate structure, and selected uniformly for the thermal and mechanical loading. It was applied with different values of temperatures and tensile load. The results was been show in Figures6, 7, 8 and 9depending on applied temperature, tensile load, fiber orientation and fiber volume fraction.

It is seen from these figures 6 and 7 that the total strain values in longitudinal direction smoothly increases with the increase of temperature difference and tensile load. This is due to increase in the stress in longitudinal direction result from combined loads (thermal and tension) while, the total strain values in transverse direction decreases with the increase of temperature and loads, because, the transverse strain increases with temperature increase and decreases with the increase of the load, due to effect of Poisson's ratio of the plate and the dominant effect for load.

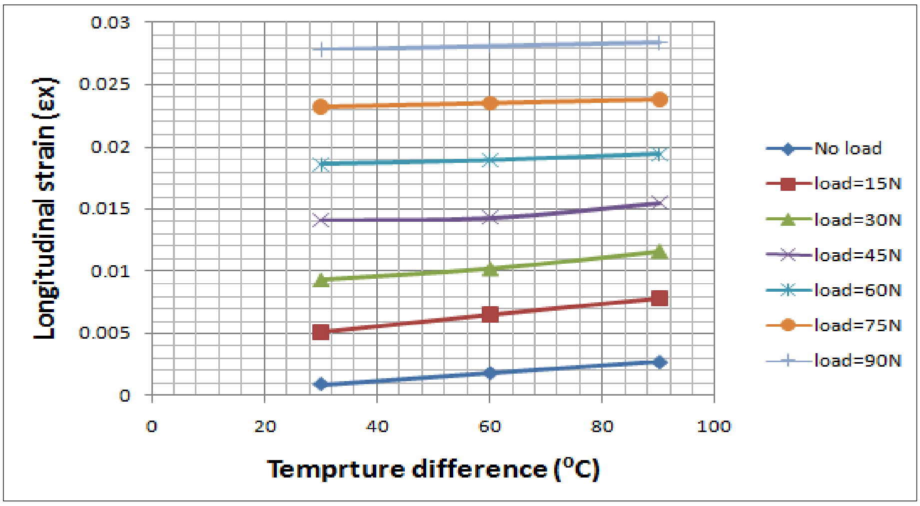


Fig. (6) Total longitudinal strain with temperatures tension load variations

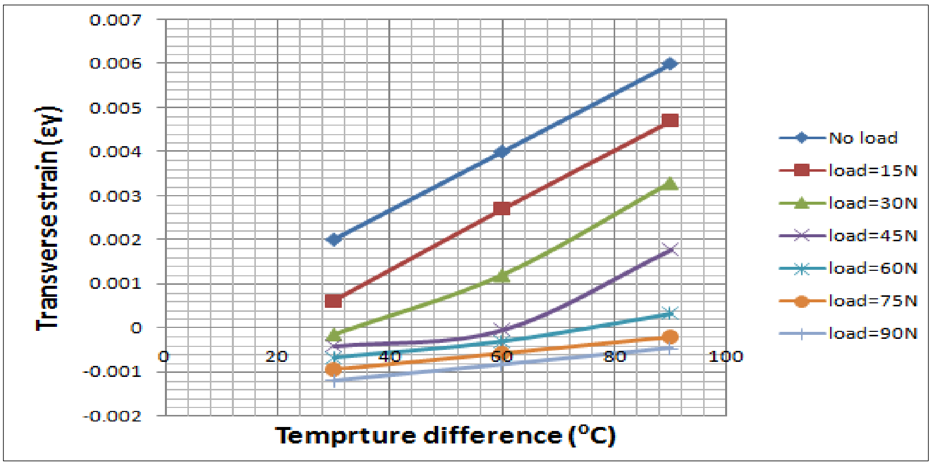


Fig. (7) Total transverse strain with temperatures tension load variations

Other important point in this figure 8 has observed that, the magnitude of total strain values in longitudinal direction has increased with the increasing of tension load and with angle of fiber until to reach angle 60° and then starts to decrease. Therefore the maximum absolute of total strain in longitudinal direction occurred at 50 N tension load and fiber angle 60°, while the minimum absolute values of it are obtained at 15 N tension loads and fiber angle 0°, Because deformation increases when the load is in the direction of the fiber, it is lower when the load is in the direction vertically on the fiber.

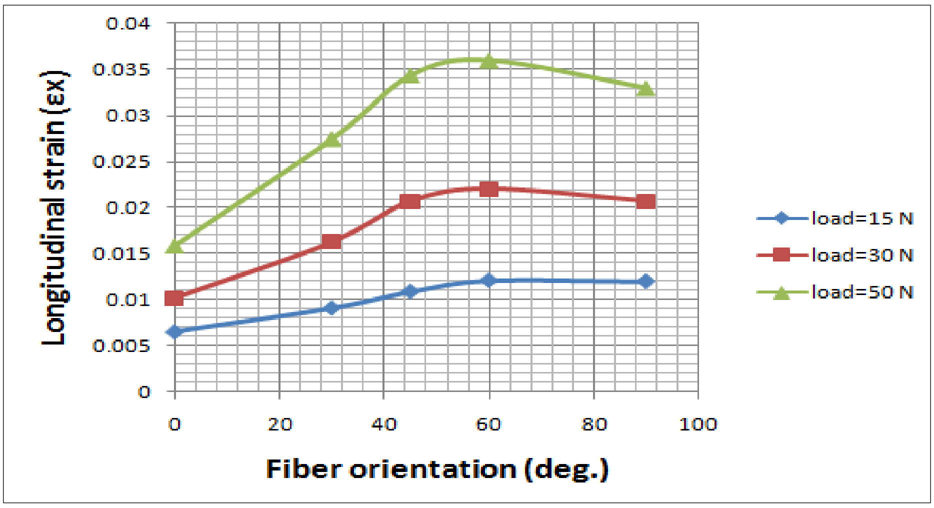


Fig. (8) Total longitudinal strain with fiber orientation at tension load variations

Additionally, another significant point in this figure 9, is the magnitude of total strain values in transverse direction has decreased with increase of tension load and with angle of fiber increase until reach angle 60° and then starts to increase, therefore the maximum absolute of total strain in transverse direction occurred at 15N tension load and fiber angle 0°, while the minimum absolute values of it are obtained at 50 N tension loads and fiber angle 60°.

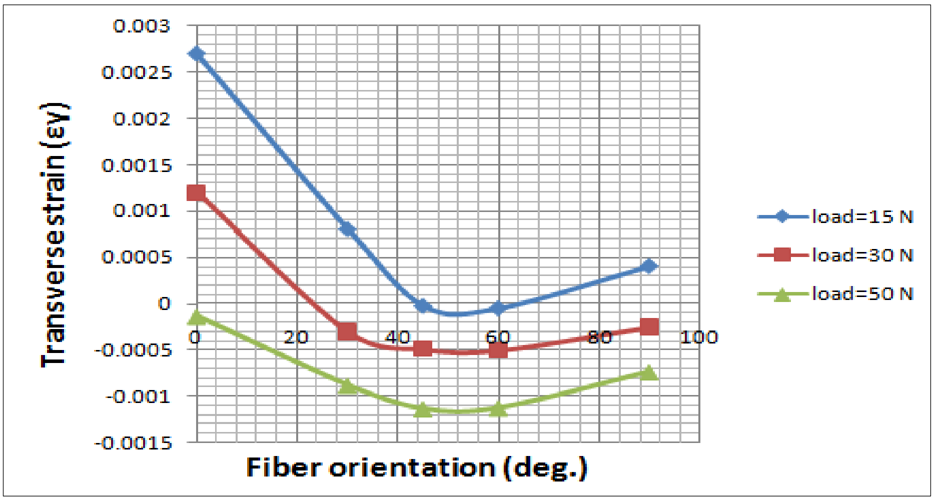


Fig. (9) Total transverse strain with fiber orientation at tension load variations

The experimental results for the orthotropic composite plate at fiber volume fraction 5% is compared with numerical analysis using Ansys program. As shown in Figures10, 11, 12, 13, and Figures 14, 15 represent the experimental results for total strain.

It is found to be reasonable in good agreement with numerical results. The percentage of the discrepancy is about 20%.

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

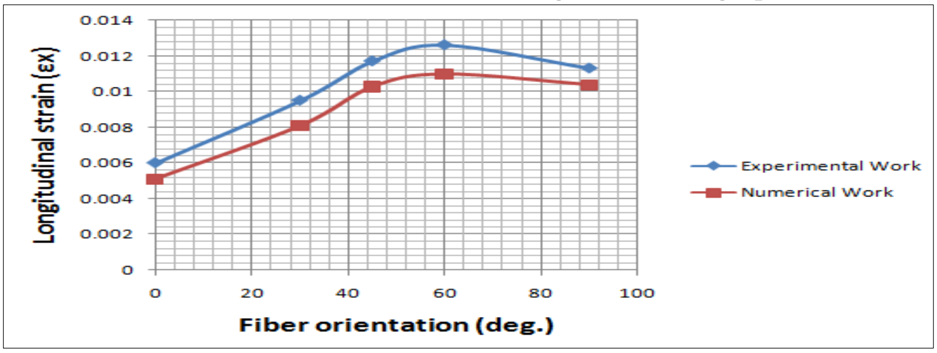


Fig. (10) Comparison of longitudinal total strain for composite plate at $\Delta T = 30$℃ and load 15N

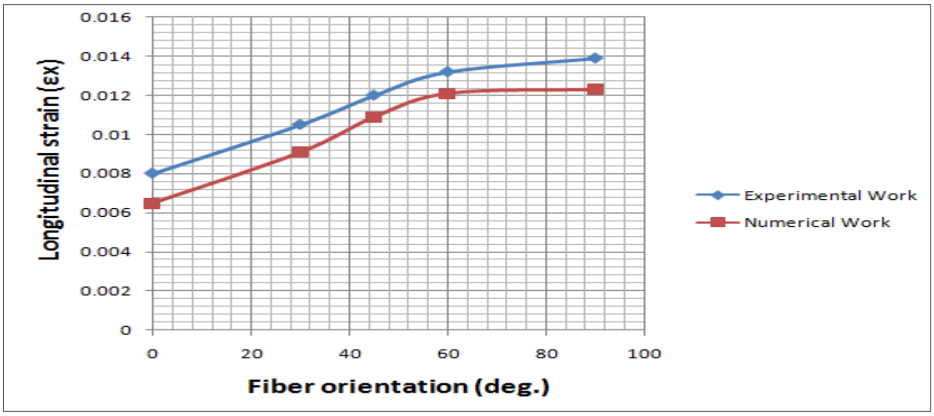


Fig. (11) Comparison of total longitudinal strain for composite plate at $\Delta T = 60$℃ and load 15N

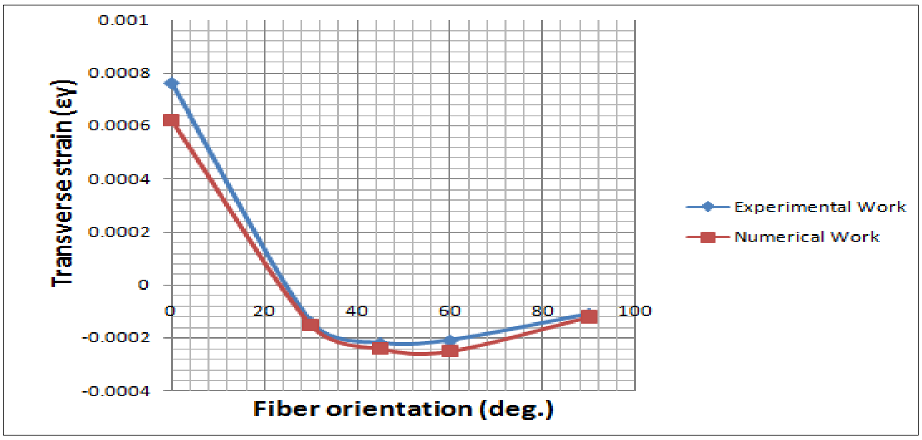


Fig. (12) Comparison of total transverse strain for composite plate at ΔT = 30℃ and load 15N

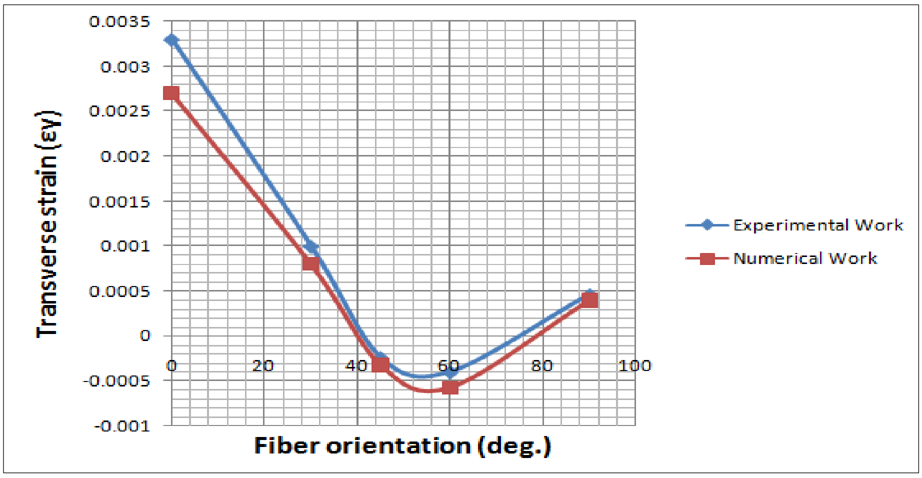


Fig. (13) Comparison of total longitudinal strain for composite plate at ΔT = 60℃ and load 15N

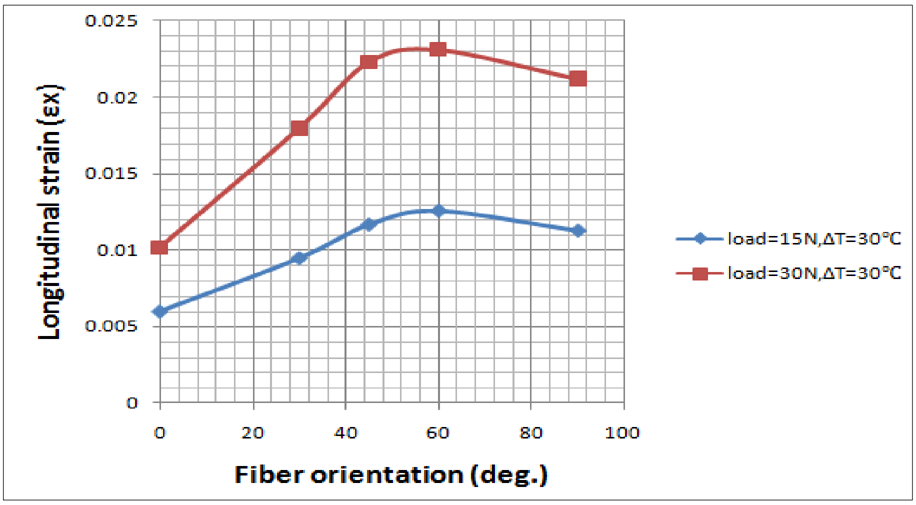


Fig. (14) Represent total longitudinal strain obtained experimental with fiber orientation at difference loads

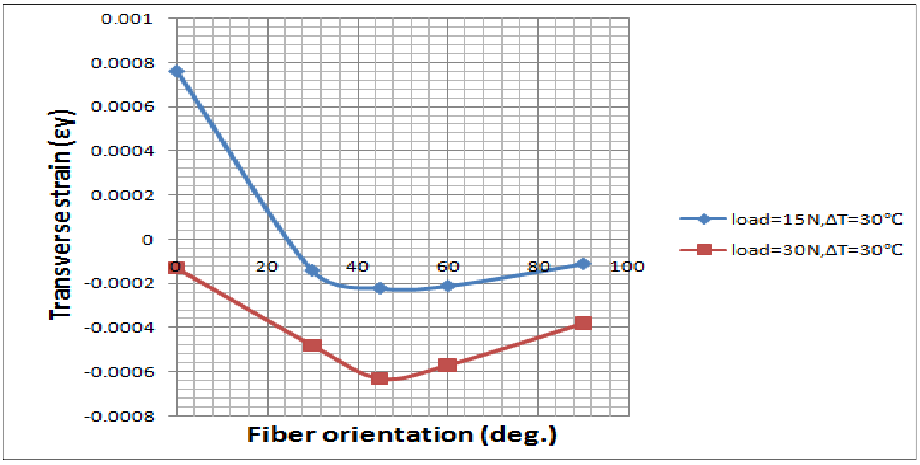


Fig. (15) Represent total strain values in transverse obtained experimental at difference loads

7. Conclusions

The following conclusions can be drawn from the above analysis:

1- Total strain in longitudinal and transverse direction decreases with increasing the fiber volume fraction.

2- The maximum absolute of total strain in longitudinal direction occurred at 50 N tension load and fiber angle 60°, while the minimum absolute values of it are obtained at 15 N tension loads and fiber angle 0°.

3- The maximum absolute of total strain in transverse direction occurred at 15N tension load and fiber angle 0°, while the minimum absolute values of it are obtained at 50 N tension loads and fiber angle 60°.

4- The variation of total longitudinal strain increase with fiber orientation increase until reach angle 60° and then starts to decrease. Whereas, the variation of total transverse strain decrease with increase fiber orientation until reach 60° and then starts to increase for all cases.

5- The results conclude that numerical and experimental values are convenient which provide the permission to use numerical strain analysis for the composite material while the maximum error is about 20%.

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