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Transient Interlaminar Thermal Stress Analysis of angle-ply Silicon/Lithium Aluminosilicate Composite plate

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Abstract:
This paper deals with the transient interlaminar thermal stress analysis of angle-ply SIC/LAS composite cantilever plate due to sudden change in the thermal boundary conditions .The transient interlaminar thermal stresses are computed by using the finite element method for different intervals of time. The effects of the fiber volume fraction, fiber orientation angle and stacking sequence are studied. The results are compared with previous studies with a good agreement.

Keywords: **Transient thermal stress, Fiber volume, Stacking sequence, FEM**

1. INTRODUCTION

Composite materials are used to produce the highest strength to weight ratio structures. The benefits of using composite materials include high strength, light weight, corrosion resistance, design flexibility and durability. The use of laminated composites allows engineers to design structural components by adjusting the orientations, thickness and stacking sequences of the fiber-reinforced lamina to provide a laminate which possesses the desired stiffness and strength. This has great advantage over the use of conventional unreinforced materials such as metals. The thermomechanical behavior of such materials especially metal and ceramic matrix composites, has received considerable attention. This is mostly because that the temperature at which the metal and ceramic composites could be utilized is much higher than that for polymer-based composites. In the analysis and design of advanced fiber composites, the problem of " free edge effect" of laminated composites has attracted considerable attention. Both experimental studies and approximate solutions have indicated that there exists highly localized regions of stress concentration near laminate free edges, due to geometrical as well as material discontinuities.

Many studies therefore, have been made on the thermal stress analysis of composite materials. Pipes and Pagano[1] first employed finite difference method to study the nature of interlaminar stresses in symmetric composite laminates due to mechanical loading. Wang and Chou[2] carried out transient thermal stress analysis in unidirectional fiber composites. Wang and etal [3] employed the study of thermal transient stresses due to rapid cooling in a thermally and elastically orthotropic medium. Hsu and Herakovich[4] used the perturbation method to obtain a zeroth-order solution for edge effects in angle-ply composite laminates subjected to a uniform strain .Wang and Chou[5] carried out the three-dimensional analysis of transient interlaminar thermal stress of cross-ply composites. Wang and Choi[6] carried out the boundary layer thermal stress analysis in angle-ply composite laminates. Kassapoglou and Lagace[7] obtained the closed-form solutions to the problem of interlaminar stress at a straight free edge of cross-ply and angle-ply laminates using the force balance method and minimum complementary energy principle. Bektas [8] performed elastic- plastic stress analysis on aluminum metal- matrix laminated plates under thermal loads varying linearly along the thickness.

In this study, transient thermal stress analysis was performed on symmetric angle-ply (Sic/LAS) aluminosilicate laminated composite plate which is subjected to sudden edge heating of the magnitude T=1°C. The interlaminar thermal stress, the fiber orientation, the fiber volume fraction and the stacking sequence have been studied. Moreover, the transient thermal effect on boundary layer stress was compared with that induced by the application of uniaxial tension.

1.1 Thermal Stress Field

A four-ply symmetric $(-\theta/\ \theta)_s$ cantilever composite laminate plate was considered in this study where the displacements are independent of the z-axis and expressed as:

$$\begin{aligned} U &= u\,(x,y,t) \\ V &= v\,(x,y,t) \\ W &= w\,(x,y,t) \end{aligned} \tag{1}$$

The time variable (t) will not be written out for convenience in the following discussion. The equilibrium equations are:

$$\begin{aligned} &\partial\sigma_x/\partial x + \partial\tau_{xy}/\partial y + \partial\tau_{xz}/\partial z = 0 \\ &\partial\tau_{xy}/\partial x + \partial\sigma_y/\partial y + \partial\tau_{yz}/\partial z = 0 \\ &\partial\tau_{xz}/\partial x + \partial\tau_{yz}/\partial y + \partial\sigma_z/\partial z = 0 \end{aligned} \tag{2}$$

The stress-strain relations for orthotropic materials are [9]

$$\begin{aligned} \sigma_x &= c_{11}\epsilon_x + c_{12}\epsilon_y + c_{13}\epsilon_z + c_{16}\gamma_{xy} - \beta_1 T \\ \sigma_y &= c_{12}\epsilon_x + c_{22}\epsilon_y + c_{23}\epsilon_z + c_{26}\gamma_{xy} - \beta_2 T \\ \sigma_z &= c_{13}\epsilon_x + c_{23}\epsilon_y + c_{33}\epsilon_z + c_{36}\gamma_{xy} - \beta_3 T \\ \tau_{yz} &= c_{44}\gamma_{yz} \end{aligned} \tag{3}$$

$$\begin{aligned} \beta_1 &= \alpha_x c_{11} + \alpha_y c_{12} + \alpha_z c_{13} + \alpha_{xy} c_{16} \\ \beta_2 &= \alpha_x c_{12} + \alpha_y c_{22} + \alpha_z c_{23} + \alpha_{xy} c_{26} \\ \beta_3 &= \alpha_x c_{13} + \alpha_y c_{23} + \alpha_z c_{33} + \alpha_{xy} c_{36} \end{aligned} \tag{4}$$

1.2 Properties of the Composite Material

A cantilever composite plate is made from Sic fiber-reinforced Lithium alumino silicate whose properties are listed in **Table (1)** and the properties of the matrix is shown in **Table (2)** [10].

1.3 The Rule of Mixtures

The rule of mixtures which is used to predict the composite elastic and properties from the fiber and matrix properties is as follows [10],

$$E_1 = E_{f1}V_f + E_mV_m \qquad E_2 = E_3 = E_m/[1 - \sqrt{V_f}\left(1 - \frac{E_m}{E_{f2}}\right)]$$

$$G_{12} = G_{13} = G_m/[1 - \sqrt{V_f}\left(1 - \frac{G_m}{G_{f12}}\right)]$$

$$G_{23} = G_m/[1 - \sqrt{V_f}\left(1 - \frac{G_m}{G_{f23}}\right)]$$

$$\nu_{12} = \nu_{13} = \nu_{f12}V_f + \nu_mV_m$$

$$\nu_{23} = \nu_{32} = \frac{E_2}{2G_{23}} - 1$$

$$\nu_{31} = \nu_{21} = E_2\nu_{12}/E_1$$
$$\alpha_1 = \left(\alpha_{f1}E_{f1}V_f + \alpha_m E_m V_m\right)/E_1$$
$$\alpha_2 = \alpha_3 = \alpha_{f2}\sqrt{V_f} + \left(1 - \sqrt{V_f}\right)\left(1 + V_f \nu_m E_{f1}/E_1\right)\alpha_m \qquad (5)$$

1.4 Finite Element Modeling of the Composite Plate:

The Lithium aluminosilicate metal-matrix laminated composite plate of constant thickness (16 mm) is shown in **Fig. (1)**. In this figure, ϴ represents the angle of the fiber and orientation in the matrix,the plate is fixed at one end. The length and the width of the plate is 100 and 100 mm respectively. In order to simulate the effect of interlaminar thermal stress (σ_y) for different intervals of time and the effect of the fiber orientation, the fiber volume fraction and the stacking sequence, the ANSYS- 11. Finite element analysis software package [8] is used. This software is able to calculate the behavior of composite structures with anisotropic non-linearties. (Solid191 which is a layered version of the 20 node structural solid design to model layered thick shells or solids. The element is defined by 20 nodes having three degrees of freedom per node) is used for modeling the laminated composite solid with material non-linearities. The laminate is meshed into (2482) elements and (4389) nodes schematic finite element model of the plate in ANSYS-11 as shown in **Fig. (2).**

1.5 Verification of the FEM Solution

In order to validate the accuracy and applicability of the present FEM solution, the transient thermal effect in the boundary layer for the present analysis is compared with that induced by uniaxial tension for a $(45deg/-45deg)_s$ graphite/epoxy laminate[4].It can be seen that from **Fig. (3)** that the interlaminar normal stress approaches zero away from the boundary layer and increases sharply as approaches to the free edge for both cases.

2. RESULTS AND DISCUSSION

It is assumed that the (-45deg/45deg) SIC/LAS is subjected to a sudden edge heating of magnitude T_0=1℃.

The transient interlaminar normal stress **(σ_y)** *and interlaminar* **Shear stress (τ_{yz})**

The transient interlaminar normal stress distribution of the $(-45deg/45deg)_s$ SIC/LAS which is subjected to a sudden edge heating of the magnitude T_0 =1℃ is demonstrated in **Fig. (4)**.It is apparent that the interlaminar normal stress increases very significantly for different interval times as approaches to the boundary. This indicates the existence of high stress concentration near the boundary layer. As the heating proceeds, the overall interlaminar normal stress increases smoothly, but the stress which is very close to the boundary remains almost constant. The transient interlaminar normal stress tends to zero away from the free edge of the plate.

The transient thermal interlaminar shear stress (τ_{yz}) as shown in **Fig. (5)** is small compared to the interlaminar normal stress.

2.1 The effect of fiber volume fraction

The fiber volume fraction effect is shown in **Fig. (6)** .The interlaminar normal stress increases significantly with the fiber volume fraction due to the increase of composite stiffness.

2.2 The effect of the fiber orientation angle

The influence of the fiber orientation angle on the interlaminar normal stress is demonstrated in **Fig. (7).** It is apparent that the interlaminar normal stress increases significantly with he increasing the angle-ply and interlaminar stress reaches its peak value when $\theta = 45deg$.

2.3 The effect of stacking sequence

The effect of the sequence on the interlaminar normal stress is studied in **Fig. (8)**. It can be seen that the magnitude of interlaminar normal stress for anti-symmetric sequence (-15/15,-45/45) is higher than that in symmetric sequence (-45/45).

2.4 The effect of transient times

The transient interlaminar normal stress distribution of $(-45/45)_s$ laminate at (x/b)=1 for different transient times is demonstrated in **Fig. (9).** It is shown that the stress variation for different times is slightly small, because the sudden temperature remains constant.

3. CONCLUSIONS

Transient interlaminar thermal stress analysis of laminate composite plate has been carried out by using FEM. The dependence of the interlaminar thermal stress on the different interval times, fiber volume fraction, fiber orientation angle and stacking sequence has been investigated.

1. The magnitude of the interlaminar thermal stress(σ_y) increases for different interval times.
2. The interlaminar thermal shear stress is small compared with the interlaminar normal stress.
3. The interlaminar normal stress increases with fiber volume fraction due to the composite stiffness increases.
4. The magnitude of the interlaminar normal stress for anti-symmetric stacking sequence is higher than that for symmetric sequence.
5. The interlaminar normal stress reaches its maximum value at ϴ=45deg for$(-\Theta/\Theta)_s$ laminates .

4. REFRENCES

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NOMENCLATURES

Symbols	**Description**
Sic	silicon fiber
Las	lithium aluminosilicate
ρ	density
E_1	axial young's modulus
E_2	transverse young’s modulus
G	shear young’s modulus
ν	Poison’s ratio
α	Thermal expansion coefficient
f	fiber
m	matrix
V	volume
Ɵ	fiber orientation angle
σ	normal stress
τ	shear stress
c_{ij}	Elastic stiffness constant
T	transient temperature

Table (1): The properties of the composite material

Material	ρ (g/cm^3)	E (Gpa)	G (Gpa)	ν	A (1/℃)
LAS	2.42	85	35	0.22	1

Table (2): Properties of the matrix

Material	ρ (g/cm^3)	E1 (Gpa)	E2	G12 (Gpa)	G23 (Gpa)	ν_{12}	ν_{23}	$\alpha_1(1/°C)$	$\alpha_2(1/°C)$
Sic	3.2	406	406	169	169	0.2	0.2	5.2	5.2

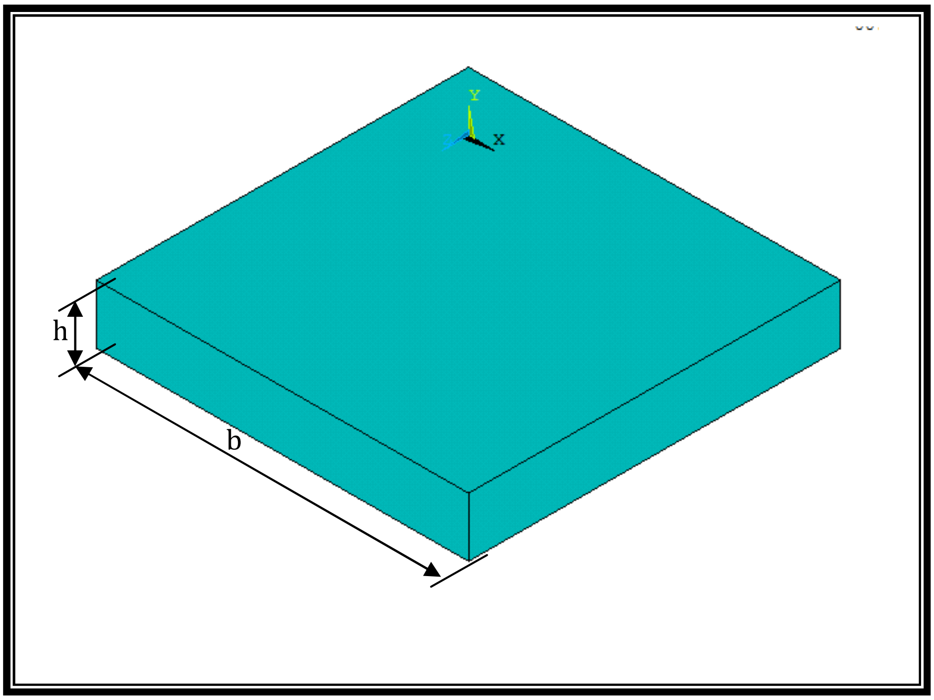

Fig. (1): SIC/LAS metal matrix composite laminate Square plate

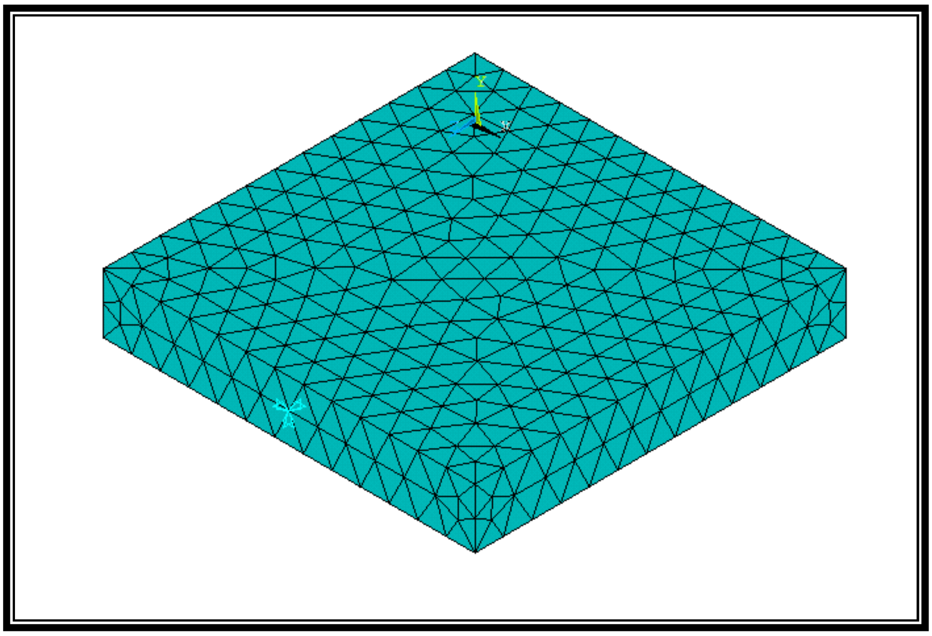

Fig. (2): Schematic finite element model in ANSYS

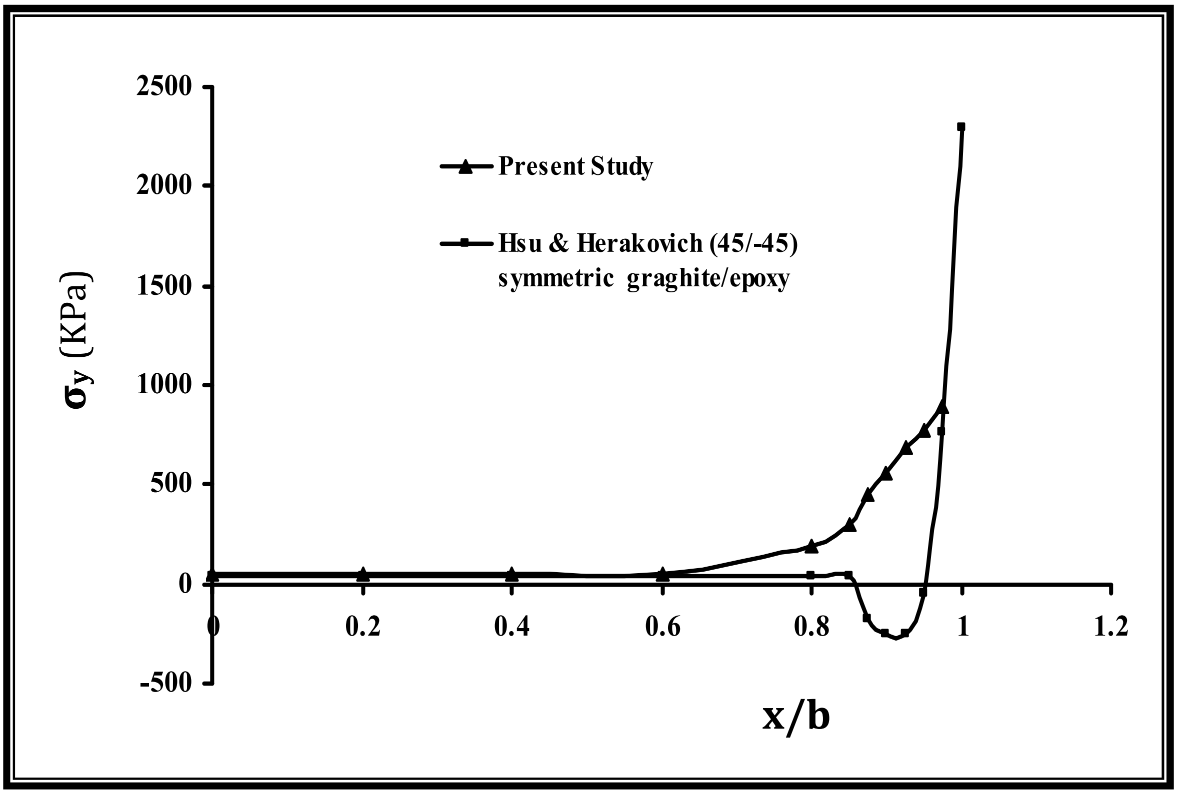

Fig. (3): comparison of transient thermal effect and axial tension

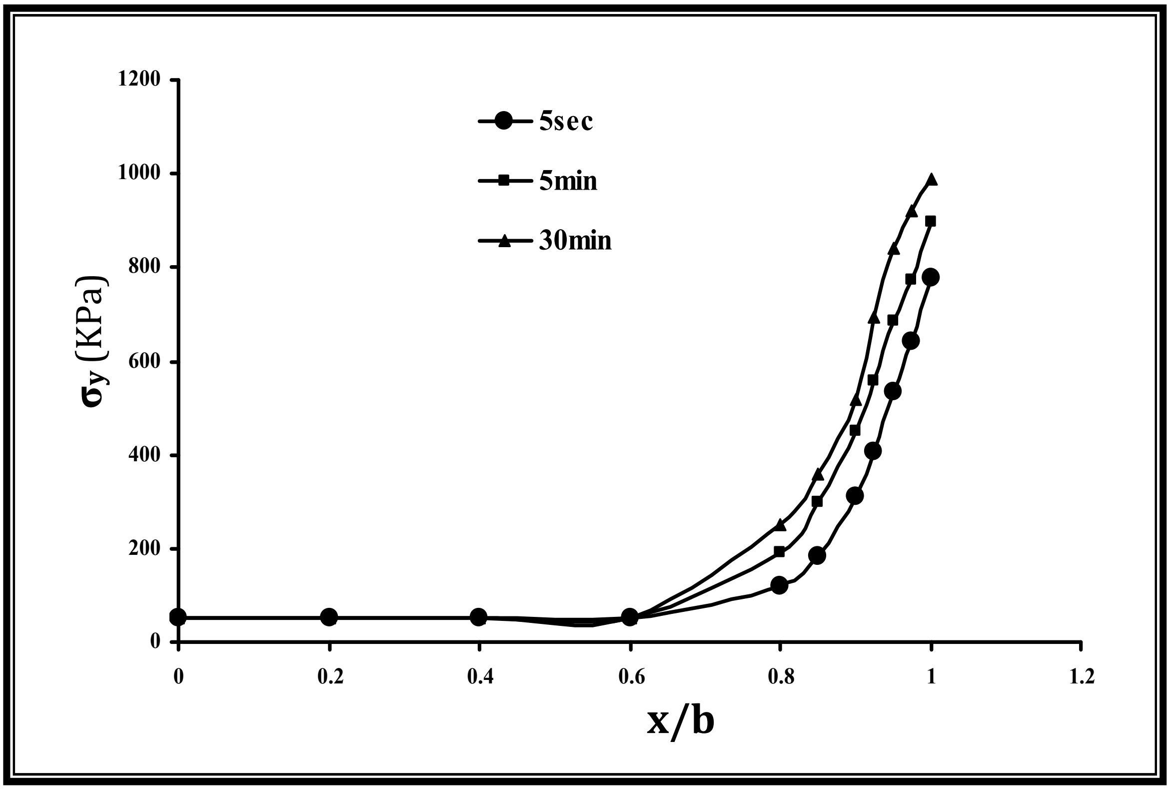

Fig. (4): Transient interlaminar thermal normal stress of sic/LAS $(-45/45)_s$ laminate for V_f =30% and T_o=1°C

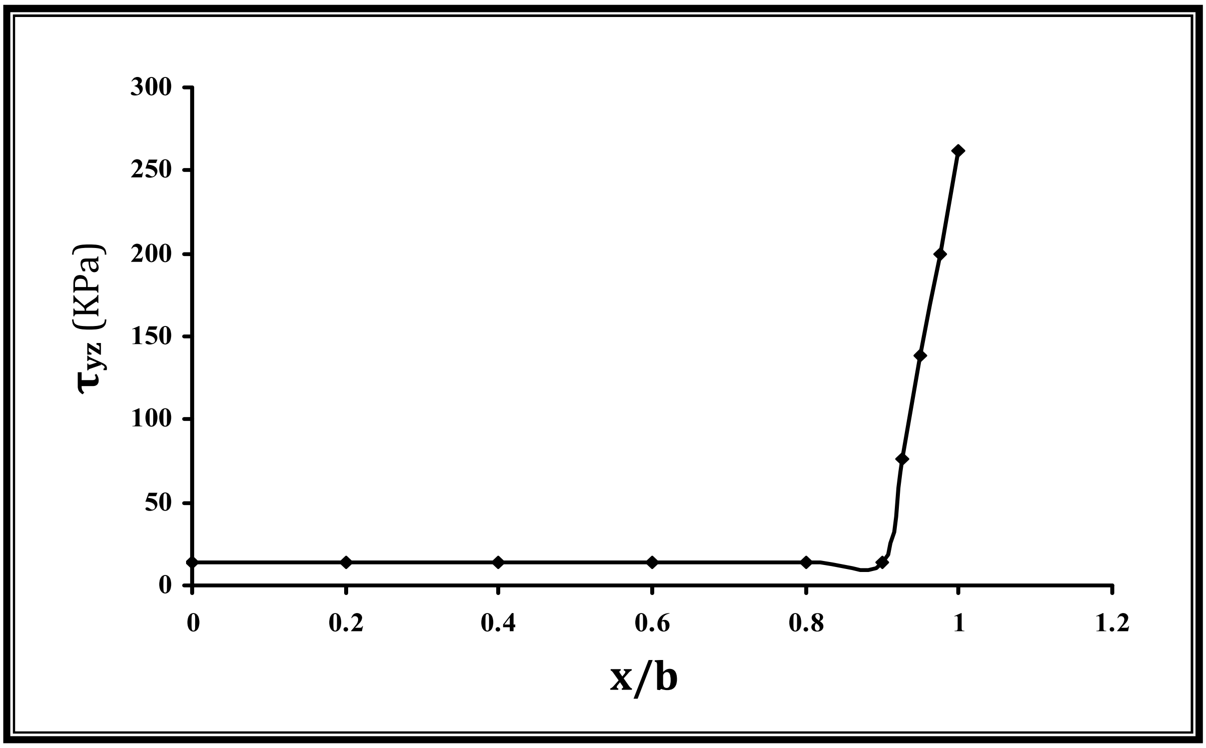

Fig. (5) : Transient interlaminar thermal shear stress of sic/LAS (-45/45)$_s$ laminate for V_f =30% and T_o=1°C

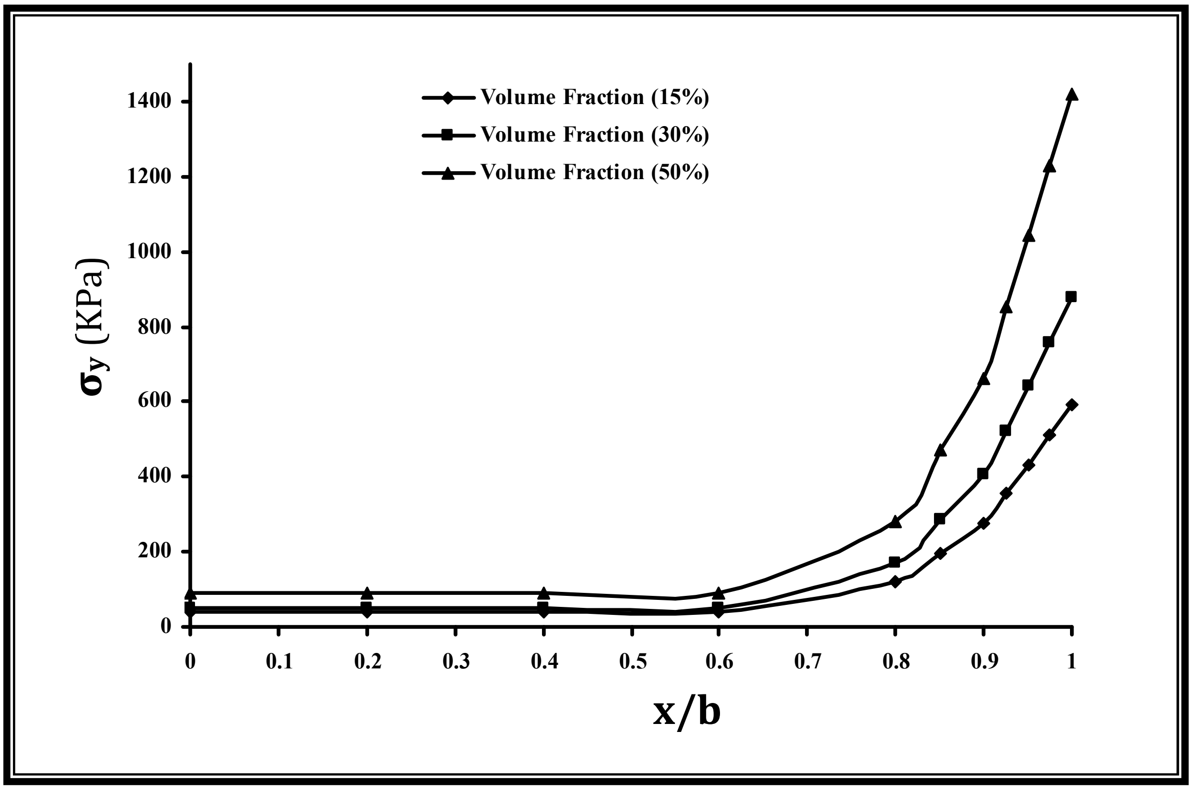

Fig. (6): Fiber volume fraction effect on interlaminar normal sress for SIC/LAS (-45/45)$_S$ at T_o= 1°C and t=2min

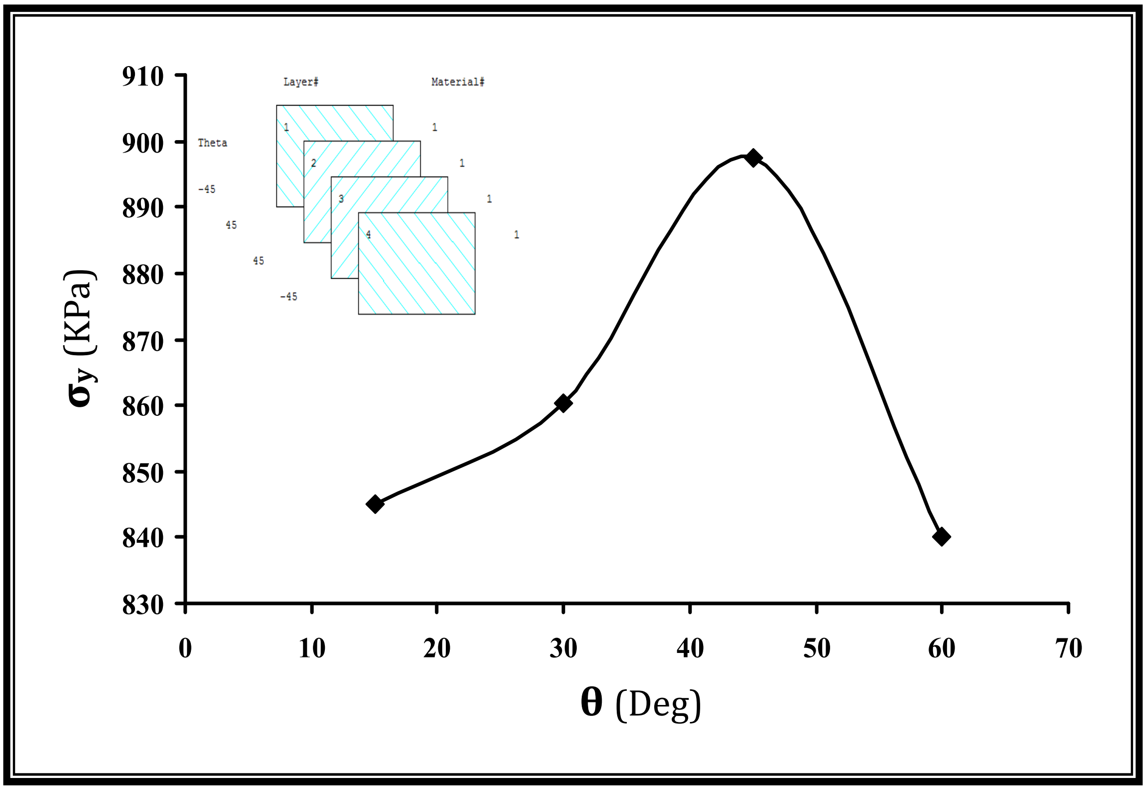

Fig. (7): Fiber orientation effect on interlaminar normal stress for a SIC/LAS $(-\theta/\theta)_s$ at T_o=1°C , t=5min, V_f=30% and (x/b)=1

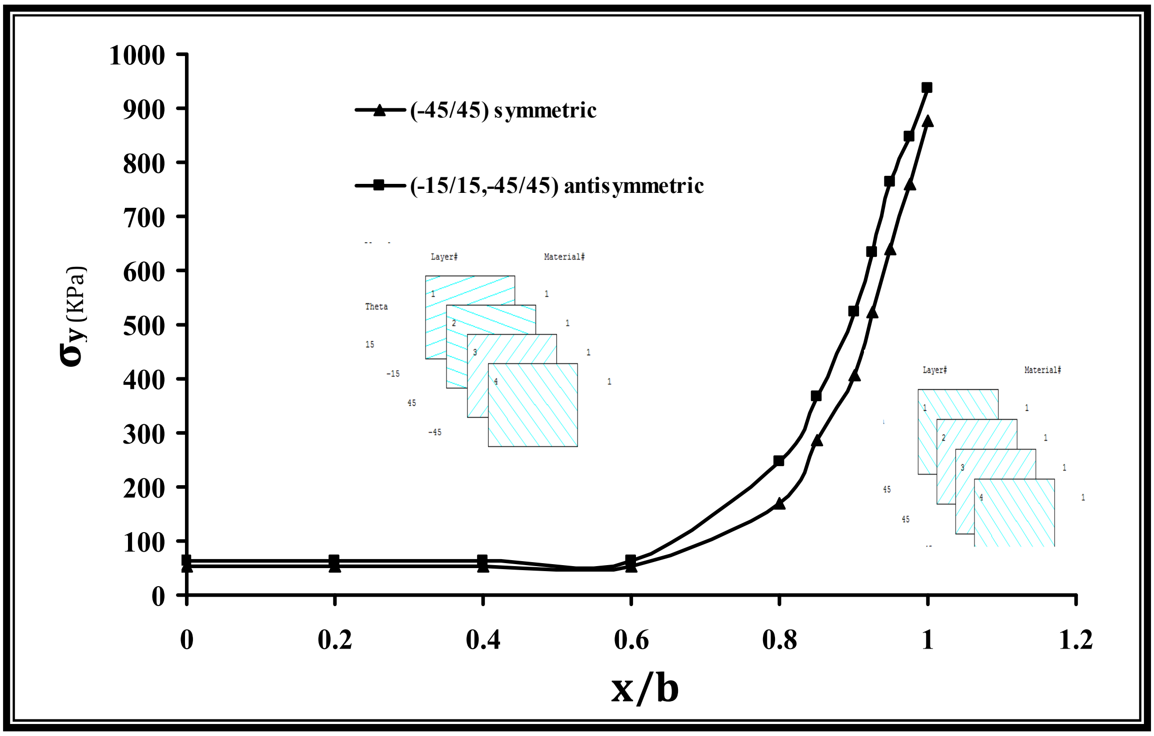

Fig. (8): The effect of stacking sequence on interlaminar normal stress for sic/LAS $(-45/45)_s$ and (-15/15 , -45/45) anti-symmetric laminate at T_o =1°C, t =5min , V_f =30%

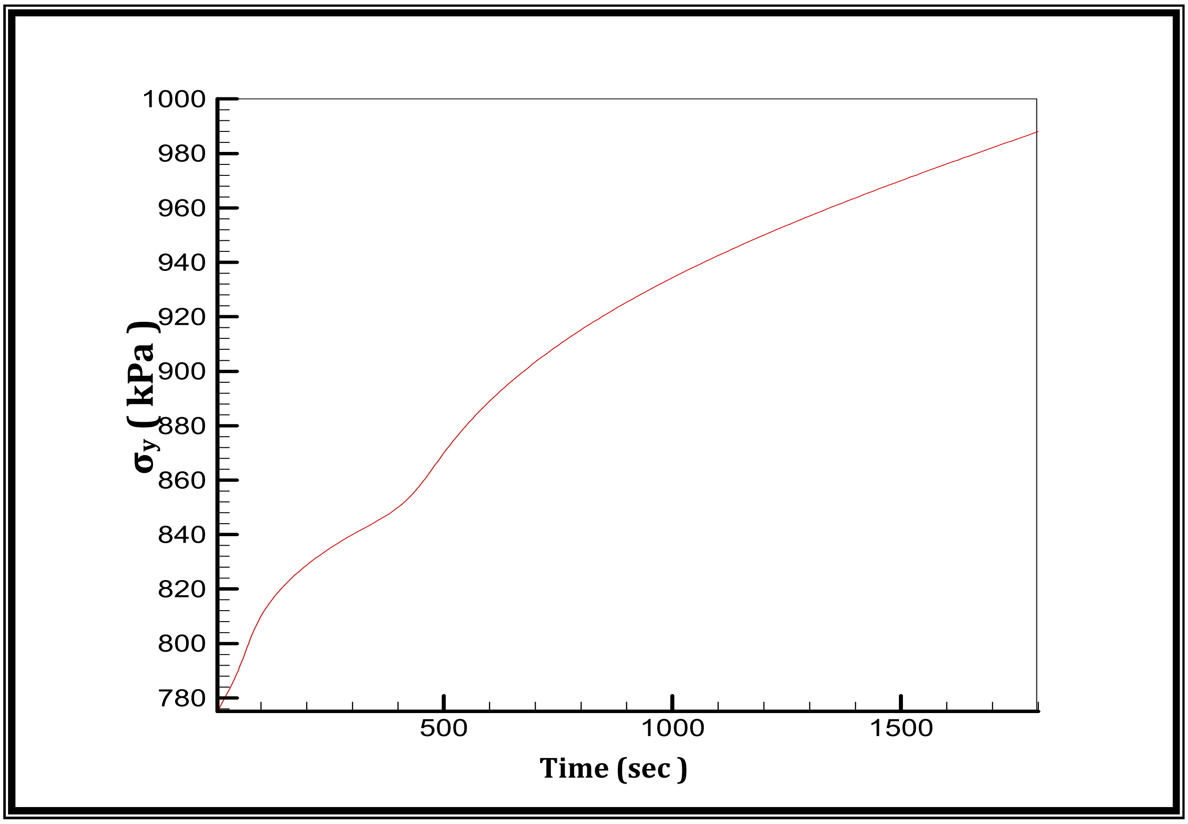

Fig. (9): Transient interlaminar thermal stress of sic/LAS $(-45/45)_s$ laminate for (x/b)=1

تحليل الاجهادات الحرارية العابرة الطبقية لصفيحة مركبة سيلكون / ليثيوم الومنسيلكات

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الخلاصة:

يتعامل هذا البحث مع تحليل الاجهادات الحرارية الطبقية العابرة على صفيحة مركبة مثبتة من طرف واحد نتيجة التغير المفاجئ في الظروف الحرارية المحيطة. ان الاجهادات الحرارية الطبقية العابرة تم الحصول عليها باستخدام طريقة العناصر المحددة لفترات زمنية مختلفة. وقد تم دراسة تأثيرات نسبة حجم الالياف في الصفيحة وزاوية اتجاة الالياف وتسلسل الطبقات. وعند مقارنة الدراسة الحالية مع دراسة اخرى وجد بان هنالك توافق جيد بين كلا الدراستين.