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Experimental Study of Flexural Strength of Laminate Composite Material

Dr. Jawad Kadhim Uleiwi*
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Abstract

The effect of fiber volume fraction on the flexural properties of the laminated composite test specimens constructed of two layers, one of them reinforced with glass fiber and the other layer reinforced with Kevlar fiber has been investigated experimentally.

The results illustrate that tension stress decreases with the increase in fiber volume fraction of glass fiber of the lower layer while it increases with the increase of Kevlar volume fraction of the upper layer. As for compression stress, it increases with the increase in volume fraction of glass fiber of the lower layer while it decreases with the increase of volume fraction of Kevlar fiber of the upper layer.

The results also show the maximum value of tension stress (= 25.3 MPa.) at V_f of Glass fiber (= 15 %) and V_f of Kevlar fiber (= 60 %), while the maximum value of compression stress (= -17.1 MPa.) at V_f of Glass fiber (= 60 %) and V_f of Kevlar fiber (= 15 %).

الدراسة العملية لاجهادات الأنحناء لمادة مركبة صفائحية

الخلاصة

أجري البحث عمليا" لدراسة تأثير الكسر الحجمي للألياف على خواص الأنحناء لعينات فحص مادة صفائحية معمولة من طبقتين، احدى هاتين الطبقتين مقواة بألياف الزجاج والطبقة الاخرى مقواة من الياف الكفلر.

بينت النتائج بان أجهاد الشد يقل مع زيادة الكسر الحجمي لألياف الزجاج للطبقة السفلى، بينما يزداد مع زيادة الكسر الحجمي لألياف الكفلر للطبقة العليا. وأن اجهاد الضغط يزداد مع زيادة الكسر الحجمي لألياف الزجاج للطبقة السفلى بينما يقل مع زيادة الكسر الحجمي لألياف الكفلر للطبقة العليا.

كما بينت النتائج بان أعلى قيمة لأجهاد الشد (= 25.3 MPa.) عند V_f لألياف الزجاج (= 15 %) و V_f لألياف الكفلر (= 60 %) ، بينما أعلى قيمة لأجهاد الضغط (= - 17.1 MPa.) عند V_f لألياف الزجاج (= 60 %) و V_f لألياف الكفلر (= 15 %).

Notation:

b	Thickness (m).
E_1	Modulus of elasticity parallel to the fiber direction (N/m^2)
E_2	Modulus of elasticity perpendicular to the fiber direction (N/m^2)
E_f	Modulus of elasticity of the fiber material (N/m^2)
E_i	Modulus of elasticity of each layer (N/m^2)
E_m	Modulus of elasticity of the matrix material (N/m^2)
h_i	Height of the layer i (m)
I	Moment of inertia (m^4)
L	Length of the specimens (m)

* Mat. Eng. Dept./ University of Technology

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

- M Bending Moment (N.m)
- n Number of layer
- P Applied load (N)
- R Radius of curvature (m)
- S Equivalent stiffness ($N.m^2$)
- V_f Volume fraction of the fiber (%)
- V_i Volume fraction of each layer (%)
- V_m Volume fraction of the matrix (%)
- Y Distance from bottom outer surface to a certain level distance (m)
- y_o Distance from bottom outer surface to neutral axis (m)
- ε_i Strain components
- σ_i Stress components (N/m^2)

Introduction

In general the flexural strength of the laminate composite beam can be improved considerably by the addition of fibers with a certain volume fraction of each layer.

Unidirectional fiber-epoxy matrix laminate composites are commonly used for advanced applications, such as blade, the flexural strength represents the major forms of loading for this type of components. Here the bending test is used to test and evaluate the strength properties of laminate composite materials with constant span–to–thickness ratio and constant width–to-thickness ratio.

The flexural strength is also known as bending strength. It describes how much of a non-moving load can be applied before a specimen yields or breaks, or it is the resistance of a material to being broken by bending stresses. High numbers mean that the material is strong and can withstand a heavy load.

The composite used in this study was unidirectional laminate material (glass fiber and Kevlar fiber) – epoxy matrix composite.

The unidirectional specimens were bend tested using universal material testing machine equipped with three - point loading apparatus.

The aim of this work is to evaluate the laminated composite beam made from two layers to flexural strength.

The tension stresses of the lower surface and compression stresses of the upper surface at the mid point of the laminate composite beam were measured experimentally depending on the technique of strain gauge and strain meter.

In this research the fiber volume fraction of the reinforcing layer of the laminate composite material represents the major factor on the flexural strength of the laminated composite beam.

Most of the work is concentrated on determining the stresses of the composite beam with different boundary conditions.

B.P. Hughes and N.I. Fattuhi determined the various efficiency factors for steel and polypropylene fibers in cement–based composites with particular reference to flexural specimens [1].

Yail J. Kim and Andrew Kong studied a new composite material, namely steel reinforced polymer (SRP), in flexural strengthening of rectangular reinforced concrete beams and found that increasing the flexural strength up to 53 % was achieved in the beams strengthened with SRP sheets [2].

G.J. Turvey determined the initial flexural failure loads as associated central deflections for simply supported composite plates subjected to a uniform lateral pressure [3].

J. Kosoric, M.Cattani, S. Bouill, Ch. Godin, and J. Meyer evaluated the composite reinforced with glass fibers of two dental materials: laboratory composite resins and provisional resins. The analysis showed that glass fibers reinforceing the laboratory composite resins have greater effect on the flexural strength than modulus of elasticity [4].

Zsolt R'ACZ studied the analysis of the flexural strength of the unidirectional composite carbon fiber composites and estimated the magnitude of size effect in carbon fiber composite and the result revealed that a specimen with lower span – to thickness ratio exhibits a lower flexural strength [5].

Lassila J. and Vallittu P. K. investigated the influence of the position of fiber rich layer on the flexural properties of fiber – reinforced composite construction. They found that the specimens with FRC positioned on the compression side showed flexural strength of approximately 250 MPa., while FRC positioned on the tension side showed strength ranging from 500 to 600 MPa. [6].

Johnston, C.D. and Zemp, R.W. examined the influence of fiber content (0.5-1.5 % of volume), fiber aspect ratio (47-100), and fiber type (4 types) on the flexural fatigue performance of steel fiber reinforced concrete [7].

T. Waki and T. Nakamura studied and compared the flexural strength of three types of Glass-fiber reinforced composite systems. They found that the BR-100 (686 MPa.) and vectris (634 MPa.) beams demonstrated significantly higher flexural strength than the fiber Kor (567 MPa.) beam and also found that (Estenia / BR-100) composite had a good mechanical strength for metal – free restorations [8].

Theoretical Analysis of Laminate Composite Material

Laminated fiber reinforced composite material consists of multi layers of various material and each layer is called lamina, defined as a composite made by a single layer of material, usually a flat arrangement of unidirectional fibers or woven fibers in matrix.

Lamination may also be constructed using fabric material such as cotton, paper, or woven glass fibers embedded in plastic matrix [9].

The laminate fiber reinforced composite specimen used in this research is composed of two layers of orthotropic material. The upper layer is made up of glass fiber – Epoxy matrix while the lower layer is made up of Kevlar fiber – Epoxy matrix with the same thickness for each layer but with different fiber volume fraction.

Any beam bending problem may be solved in the usual fashion except that " EI " will be replaced by the function "S" (Equivalent stiffness) computed from the values of moment of the beam so as to determine the theoretical value of deflection and stresses.

Derivation of Neutral Axis

The determination of neutral axes of laminate composite material is based on the equilibrium equation of the body. Therefore, the equilibrium can be written as [10] :-

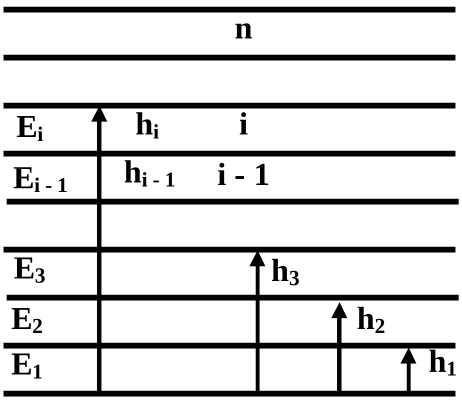
$$\int_{h_0}^{h_1} s_1 . b.\, dy + \int_{h_1}^{h_2} s_2 .\, b.\, dy + \int_{h_{i-1}}^{h_i} s_i .\, b.\, dy = 0 \quad .....(1)$$

$$s_i = E_i .\, e_i = E_i \, \frac{y - y_0}{R} \quad .....(2)$$

because $\varepsilon_i = (y - y_0)/ R$

$$\sum_{i=1}^{n} \int_{h_{i-1}}^{h_i} E_i \left(\frac{y - y_0}{R} \right) b.\, dy = 0 \quad ....(3)$$

$$\sum_{i=1}^{n} \frac{E_i . b}{R} \int_{h_{i-1}}^{h_i} (y - y_0)\, dy = 0 \quad \ldots(4)$$



$$\sum_{i=1}^{n} \frac{E_i . b}{R} \left[\frac{y^2}{2} - y_0 . y \right]_{h_{i-1}}^{h_i} = 0 \quad \ldots(5)$$

$$\sum_{i=1}^{n} \frac{E_i . b}{R} \left[\left(\frac{h_i^2}{2} - y_0\, h_i \right) - \left(\frac{h_{i-1}^2}{2} - y_0\, h_{i-1} \right) \right] = 0 \quad \ldots(6)$$

$$\sum_{i=1}^{n} \frac{E_i . b}{R} \left[\left(\frac{h_i^2}{2} - y_0\, h_i - \frac{h_{i-1}^2}{2} + y_0\, h_{i-1} \right) \right] = 0 \quad \ldots(7)$$

$$\sum_{i=1}^{n} E_i \cdot \left(\frac{h_i^2 - h_{i-1}^2}{2} \right) - y_o \sum_{i=1}^{n} (h_i - h_{i-1}) = 0 \quad \ldots.(8)$$

$$y_0 = \frac{1}{2} \frac{\sum_{i=1}^{n} E_i \left(h_i^2 - h_{i-1}^2\right)}{\sum_{i=1}^{n} E_i \left(h_i - h_{i-1}\right)} \quad \ldots.(9)$$

Determination of Bending Moment:-

$$M = \int_{h_0}^{h_1} s_1 . b . dy . y + \int_{h_1}^{h_2} s_2 . b . dy . y + - - - - + \int_{h_{i-1}}^{hi} s_i \cdot b \cdot dy \cdot y \quad \ldots(10)$$

$$\therefore M = \sum_{i=1}^{n} \int_{h_{i-1}}^{h_i} E_i . b \, \frac{y - y_0}{R}\, y . dy \quad \ldots.(11)$$

$$M = \frac{b}{6R} \sum_{i=1}^{n} E_i \left[2\left(h_i^3 - h_{i-1}^3\right) - 3 y_0 \left(h_i^2 - h_{i-1}^2\right) \right] \quad \ldots.(12)$$

$$S = MR = \frac{b}{6} \sum_{i=1}^{n} E_i \left[2\left(h_i^3 - h_{i-1}^3\right) - 3 y_0 \left(h_i^2 - h_{i-1}^2\right) \right] \quad \ldots..(13)$$

$$S = MR = \frac{b}{6} \sum_{i=1}^{n} E_i \left[2\left(h_i^3 - h_{i-1}^3\right) - 3 y_0 \left(h_i^2 - h_{i-1}^2\right) \right] \quad \ldots.(14)$$

$\because$ MR = EI = S
$\because$ σ/ y = M/ I = E/ R (simple bending theory of the beam)
and S = EI = MR "equivalent stiffness"
I = bd^3/ 12

The Composite beam is simply supported, the deflection of the beam is therefore: The deflection (δ) = PL^3/ 48EI
And the stresses are:

$\sigma_{max} = M * y_{max} / I$

(may be compression or tension)

$\sigma_{min} = M * y_{min} / I$

(may be compression or tension)

Composite Material:

Some properties of the laminar composite materials in the longitudinal direction and in the lateral direction are estimated from the rule of mixtures

Modulus of elasticity in the longitudinal direction (parallel to the laminas (E_c*)*

$$E_c = \sum_{i=1}^{n} E_i \cdot V_i \qquad \ldots(15)$$

Modulus of elasticity in the lateral direction (perpendicular to the laminas (E_2*)*

$$\frac{1}{E_c} = \sum_{i=1}^{n} \frac{V_i}{E_i} \qquad ..(16)$$

On the other hand the properties of a unidirectional lamina are found by using the following equation.

$$E_1 = E_f \cdot V_f + E_m \cdot V_m \qquad ..(17)$$

$$E_2 = E_3 = \frac{E_f \cdot E_m}{E_f \cdot V_m + E_m \cdot V_f} \qquad \ldots(18)$$

Experimental Work

The experimental work was carried out in the field to determine experimentally the deflection, tension and compression stress of the test specimens.

The unidirectional fibrous composite test specimen is composed of two layers. The upper one is made from Kevlar fiber – Epoxy matrix composite and the lower one is made from glass fiber – Epoxy matrix with different fiber volume fraction for each layer as following.

V_f of Glass fiber (upper layer) = 15%, 30 %, 45 %, and 60 %.
V_f of Kevlar fiber (lower layer) = 15%, 30 %, 45 %, and 60 %.

The Geometry of the test specimen has a length of (170 mm) and width of (13 mm) and a thickness of (3.5 mm) as shown in figure (1) [11].

Figure (2) represents the three-point test machine with a test specimen of the laminated composite beam supplied with strain gauge at both faces (upper and lower face) to measure the strain from the strain gauge in order to calculate both the bending compression and the tension stresses of the faces.

Instrumentation

The following instrumentations were needed in the experimental work:

1-) Digital strain meter.
2-) Specimens equipped with strain gauges.
3-) Weights.

Results and Discussion

The results obtained from the experimental work of the flexural analysis of the laminated composite test specimen are illustrated in Table (1) which represents the position of neutral axis of the beam, deflection of the beam, compression and tension stress of the composite test specimen which is measured by using strain gauge and strain meter technique.

Figure (3) represents the schematic diagram for the thickness of the laminate composite test specimen illustrating the values of stresses (tension and compression) with the position of neutral axis at different values of glass fiber volume fraction of the upper layer and a constant value of Kevlar fiber volume fraction of the lower layer.

It is also clear from this figure that the position of neutral axis decreases with the decrease of the glass fiber volume fraction of the upper layer, where as the value of the tension stresses increases with the increase of the glass fiber volume fraction of the upper layer. As for the compression stress, it decreases with the increase of the glass fiber volume fraction.

Figure (4) shows the relationship between stress (compression and tension stress) with the volume fraction of Glass fiber of the upper layer at a constant volume fraction of Kevlar fiber (=30 %) of the lower layer.

It is clear from this figure that the tension stress resulting from the bending of the lower face decreases in nonlinear relationship from (19.8 MPa.) to (13.7 MPa.) with the increas of the glass fiber volume fraction from (15 %) to (60 %) respectively due to the increase of the reinforcing material. On the other hand, the compression stress of the upper surface increases from (-10.6 MPa.) to (-14.3 MPa.) with the increase in the glass fiber volume fraction from (15 %) to (60 %) respectively.

Figure (5) shows the relationship between the position of neutral axis (measured from the reference of the lower face) and the glass fiber volume fraction of the upper layer at different Kevlar fiber volume fraction of the lower layer.

It is clear from this figure that the fiber volume fraction of each layer influences the position of neutral axis, where the position increases in nonlinear relationship with the increase in the glass fiber volume fraction of the upper layer, while it decreases with the increase of Kevlar fiber volume fraction of the lower surface.

It is found that the position of the neutral axis (=1.12 cm) at V_f of Glass (=15 %), while (= 1.5 cm) at V_f of Glass (= 60 %) for the same value of V_f of Kevlar (= 60 %). It has also been found that the highest value of the position of the neutral axis (=2.051 cm) at V_f of Glass (=60 %) of the upper surface and V_f of Kevlar (=15 %) of the lower surface.

Figure (6) shows the 3-dimensional relationship between the lateral deflection of the laminated composite beam and the volume fraction of glass fiber and volume fraction of Kevlar fiber.

It can be seen from this figure that deflection decreases in nonlinear relationship with the increase of both glass fiber volume fraction and Kevlar fiber volume fraction.

It is found that the maximum value of deflection is (=0.85 mm) at V_f of glass (=15 %) and V_f of Kevlar (=15 %), while the minimum value of deflection is (= 0.24 mm) at V_f of Glass (= 60 %) and V_f of Kevlar (=60 %).

Figure (7) shows the 3-Dimensional relationship between tension stress of the lower face and the ratios of glass and Kevlar fiber volume fraction of each layer.

It can be seen from this figure that the tension stress of the lower face increases in nonlinear relationship with the increase in Kevlar fiber volume fraction because the Kevlar fiber reinforces the lower layer while it decreases in nonlinear relationship with the increase of glass fiber volume fraction. Also it is clear from this figure that the maximum value of the tension stress (= 25.3 MPa.) at V_f of Glass fiber (= 15 %) of the upper layer and V_f of Kevlar (= 60 %) of the lower layer, while the minimum value of tension stress (= 11.8 MPa.) at V_f of Glass fiber (= 60 %) of upper layer and V_f of Kevlar (= 15 %) of lower layer.

Figure (8) shows the 3-Dimensional relationship between compression stress of the upper face due to bending and ratios of glass and Kevlar fiber volume fraction of each layer.

It can be seen from this figure that the compression stress of the upper face decreases in nonlinear relationship with the increase of Kevlar fiber volume fraction. While it increase in nonlinear relationship with the increase of Glass fiber volume fraction. It is also clear from this figure that the maximum value of the compression stress (= -17.1 MPa.) at V_f of Glass fiber (= 60 %) of upper layer and V_f of Kevlar (= 15 %) of the lower layer, while the minimum value of compression stress (= -9.6 MPa.) at V_f of Glass fiber (= 15 %) of the upper layer and V_f of Kevlar (= 60 %) of the lower layer.

And the comparison between the theoretical results and experimental work at V_f of Kevlar fiber (= 60 %) V_f of Glass fiber (= 15 %) illustrated in table (2).

Conclusions

The main conclusions of the experimental investigation of flexural analysis of laminated composite material are:-

1- Position of neutral axis measured from the lower face increases with the increase of glass fiber volume fraction while it decreases with the increase of Kevlar fiber volume fraction.
2- The maximum value of deflection (= 0.85 mm) is at V_f of Glass (=15 %) and V_f of Kevlar (=15 %), while the minimum value of deflection (= 0.24 mm) is at V_f of Glass (=60 %) and V_f of Kevlar (=60 %).
3- Tension stress decreases from (19.8 MPa.) to (13.7 MPa.), while compression stress increases from (-10.6 MPa.) to (-14.3 MPa.) with the increase of V_f of Glass from (15 %) to (60 %) of the lower layer and at V_f of Kevlar = 30 % of the upper layer.
4- Tension stress decreases with the increase in fiber volume fraction of glass of the lower layer while increase with increase Kevlar volume fraction of the upper layer. The maximum value (= 25.3 MPa.) is at V_f of glass fiber (= 15 %) of the upper layer and V_f of Kevlar (= 60 %) of the lower layer, while the minimum value of tension stress (= 11.8 MPa.) is at V_f of glass fiber (= 60 %) of the upper layer and V_f of Kevlar (= 15 %) of the lower layer.
5- Compression stress increases with the increase of fiber volume fraction of glass of the lower layer while it decreases with the increase of Kevlar volume fraction of the upper layer. The maximum value (= -17.1 MPa.) at V_f of Glass fiber (= 60 %) of the upper layer and V_f of Kevlar (= 15 %) of the lower layer, while the minimum value of tension stress (= -9.4 MPa.) at V_f of Glass fiber (= 15 %) of the upper layer and V_f of Kevlar (= 60 %) of the lower layer.

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Table: (1) Results of Experimental Work.

Volume fraction		Position of Neutral axis * 10^-3 (m)	Deflection *10^-3 (m)	Compression Stress (MPa.)	Tension Stress (MPa.)
Kevlar Fiber	Glass Fiber				
60 %	15 %	1.12	0.49	-9.6	25.3
	30 %	1.273	0.35	-10.4	20.3
	45 %	1.4	0.28	-11.4	17.9
	60 %	1.5	0.24	-12.2	16.4
45 %	15 %	1.184	0.55	-10.9	22.8
	30 %	1.365	0.39	-11.2	18.4
	45 %	1.506	0.31	-12.2	16.4
	60 %	1.618	0.27	-13	15.2
30 %	15 %	1.294	0.65	-10.6	19.8
	30 %	1.512	0.46	-12.3	16.3
	45 %	1.668	0.37	-13.4	14.7
	60 %	1.785	0.326	-14.3	13.7
15 %	15 %	1.528	0.84	-12.4	16.1
	30 %	1.784	0.617	-14.3	13.8
	45 %	1.943	0.52	-15.8	12.6
	60 %	2.051	0.46	-17.1	11.8

Table: (2) Comparison between the Experimental Work and Theoretical Study.

	Deflection *10^-3 (m)	Compression Stress (MPa.)	Tension Stress (MPa.)
Experimentally	**0.49**	**-9.6**	**25.3**
Theoretically	**0.52**	**-10.25**	**23.8**

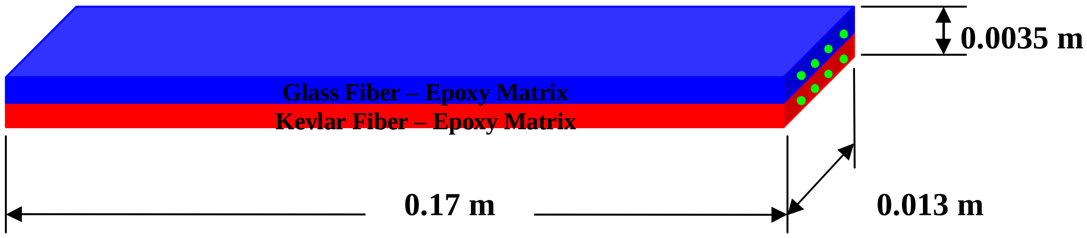

Figure (1): Test Specimen**.**

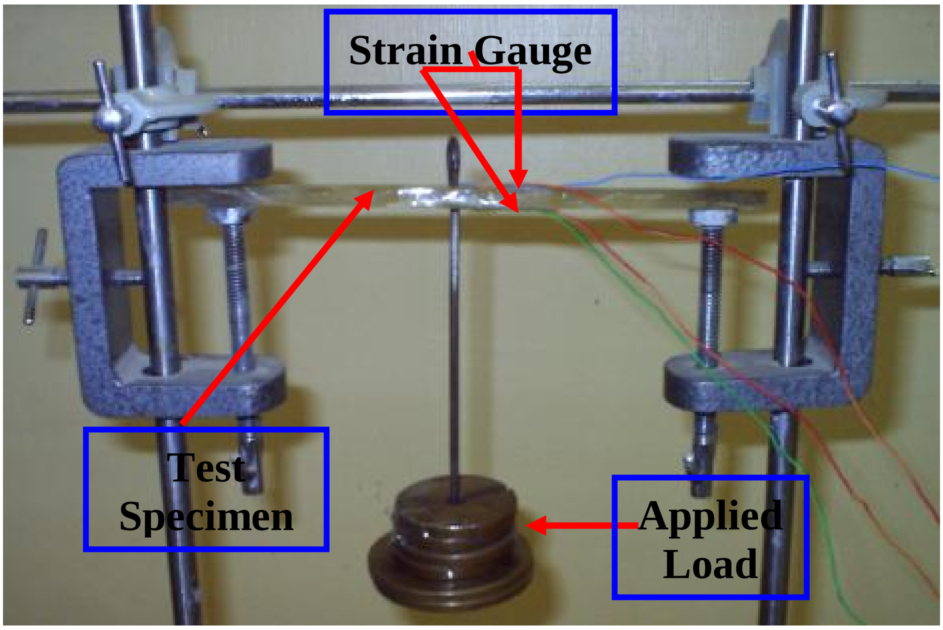

Figure (2): Flexural Apparatus with Test Specimen.

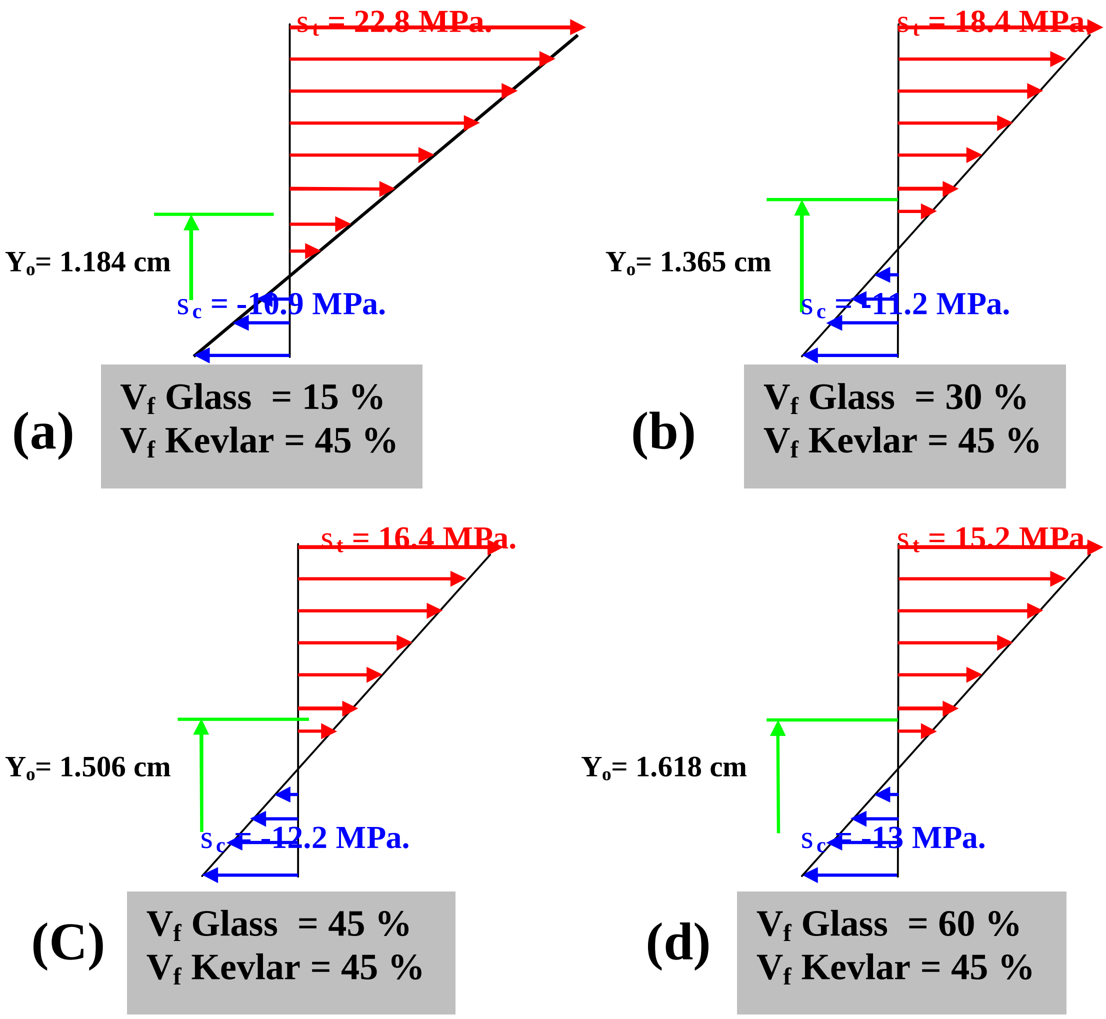

Figure (3): Schematic Diagram for Tension and Compression Stresses with Position of Neutral Axis of Laminated Composite Material at Different Fiber Volume Fraction.

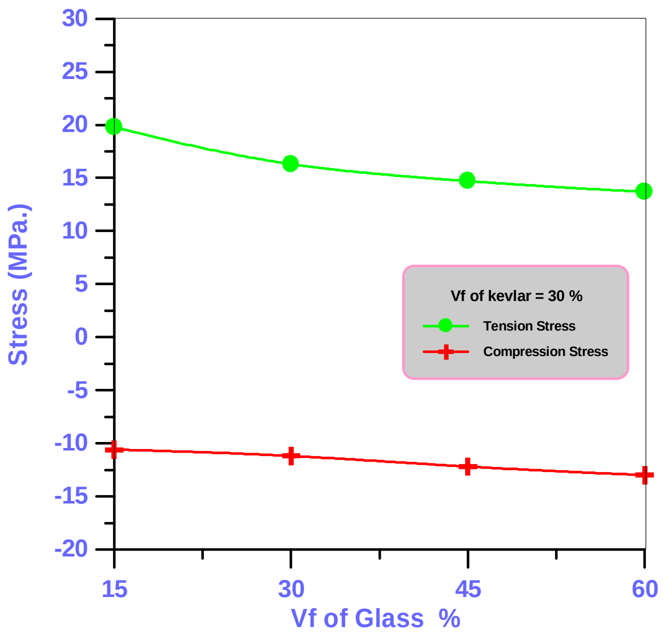

Figure (4): Relationship Between Stress (Tension and Compression) of Laminate Composite Beam and Fiber Volume Fraction of Glass at Constant Fiber Volume Fraction of Kevlar = 30 %.

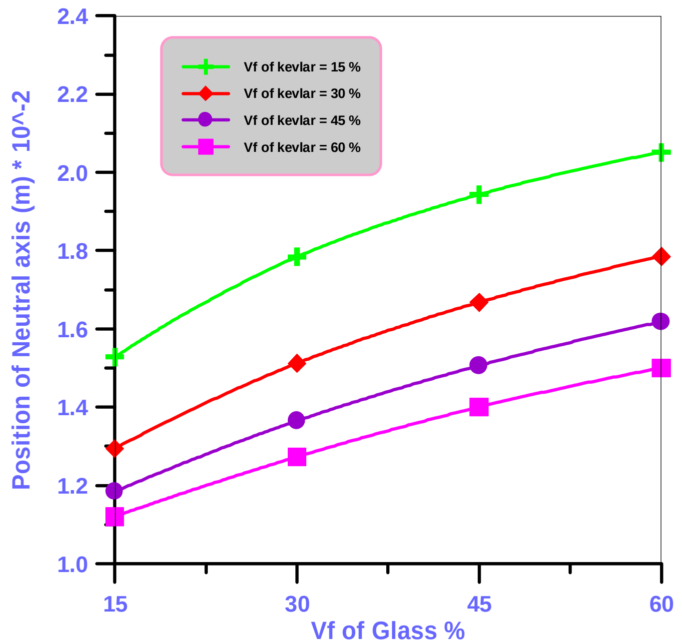

Figure (5): Relationship Between Position of Neutral Axis of the Laminate Composite Beam and Fiber Volume Fraction of Glass at Different Fiber Volume Fraction of Kevlar.

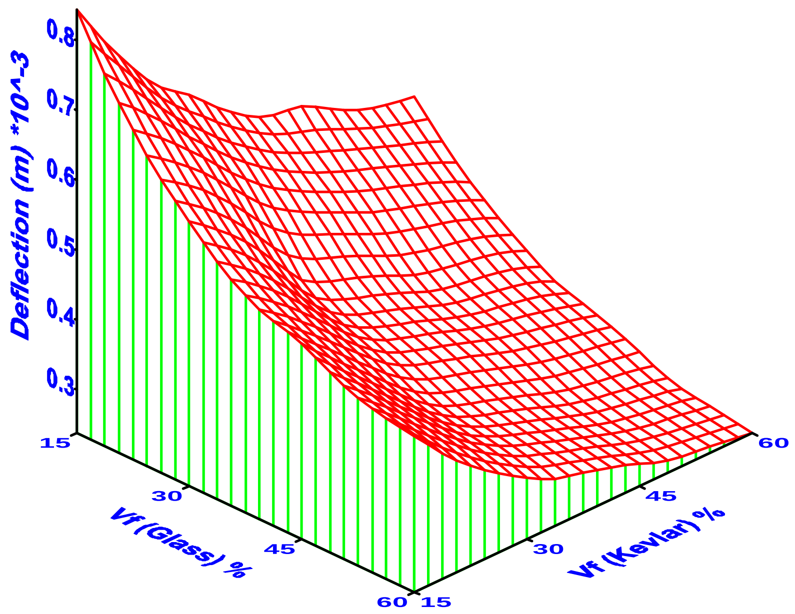

Figure (6): 3-Dimensional Relationship Between Deflection of the Laminate Composite Beam, Fiber Volume Fraction of Glass and Fiber Volume Fraction of Kevlar.

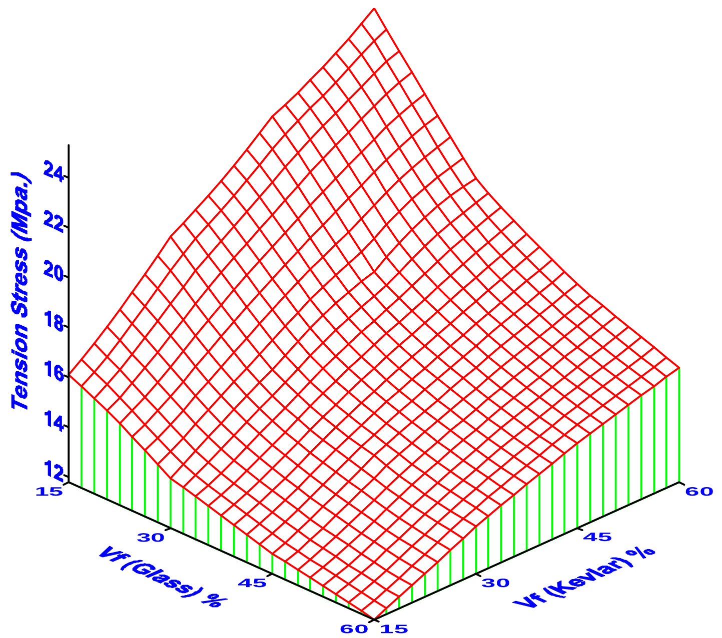

Figure (7): 3-Dimensional Relationship Between Tension Stress, Fiber Volume Fraction of Glass and Fiber Volume Fraction of Kevlar.

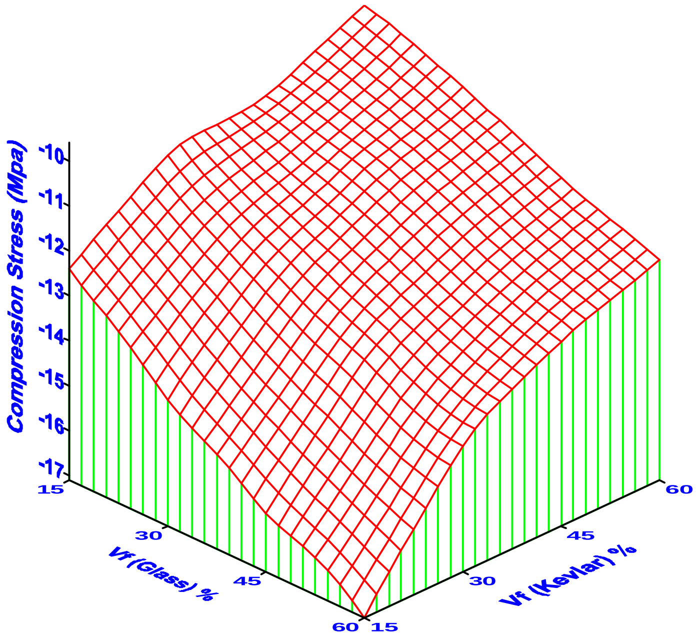

Figure (8): 3-Dimensional Relationship Between Compression Stress, Fiber Volume Fraction of Glass and Fiber Volume Fraction of Kevlar.