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EFFECT OF SHEAR MODULAR RATIO (G_F/G_M) AND TRANSVERSE SHEAR MODULUS ON THE TWISTING STRENGTH OF A FIBER-REINFORCED COMPOSITE ROD

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ABSTRACT:

In this research, the effect of shear modular G_{23} variation is investigated on the twisting strength of a unidirectional fiber reinforced composite rod subjected to various uniform static twisting moments. An optimization of the best modular ratio is also made to determine the maximum allowable twisting strength. The problem is simulated by the software of ANSYS v12 to determine the stress fields distribution throughout rod domain and the section of highest shear stresses in different planes (critical sections), a graphical representation has been made to the results obtained from a finite element analysis to rod of interest. The elastic properties of the composites investigated are found using the rules of mixtures and Halpin-Tsi equation along with the sftware of Matlab v6.5. Various types of fibers and matrices are used to change the shear modulus of G_{23} . It is found that most dominant effect is that of matrices whose the increase of its shear modulus (G_m) is getting inversely proportional to angle of twist (θ) according to a certain polynomial function of a second degree and there is a minor effect of fibers on it. The results of the analysis made by the package of ANSYS v12 were compared with the analytical solution showing the same behavior and reasonably convergent values.

الخلاصة :

تم في هذا البحث دراسة تاثير تغير{ نسبة المعاملات القصية ل(الليف/النسيج الاساس) ومعامل القص العرضي G_{23}} على مقاومة (متانة) اللي لعمود مصنوع من مادة مركبة مقواة بالياف احادية الاتجاه متوازية خاضعة لعزوم ستاتيكية. كما تم اجراء مفاضلة لتحديد افضل نسبة معاملات قصية لاكبر متانة لي ممكنة للعمود من الناحية الماكروميكانيكية. تم محاكاة المسالة بواسطة برنامج الانسز اصدار 12 لايجاد شكل وتوزيع مناطق الاجهادات وشدتها في العمود، لتحديد المقطع ذي الاجهاد الاعلى في المستويات المختلفة (المقاطع الحرجة). حسبت الخواص الميكانيكية المرنة للمواد المركبة التي تمت دراستها بواسطة قوانين المخاليط ومعادلة هالبن-تساي ومن خلال برنامج الماتلاب اصدار 6.5. وجد ان التاثير الاكبر في السلوك تحت حمل اللي يكون للنسيج الاساس والذي كانت الزيادة في معامل قصه (G_m) تتناسب عكسيا مع زاوية اللي وفقا لدالة متعددة الحدود من الدرجة الثانية وان هنالك تاثيرا اقل للالياف على ذلك السلوك. تمت مقارنة نتائج التحليل المنجز ببرنامج الانسز اصدار 12 مع الحل التحليلي بواسطة المعادلات النظرية فوجد ان هنالك تقارب كبير بالنتائج واظهرت المواد نفس السلوك الذي اظهرته في الحل العددي بواسطة برنامج الانسز اصدار 12.

KeyWords: Torsion, modulus of rigidity of matrix (G_m), fiber-reinforced composite rod, twisting strength.

1. INTRODUCTION:

As the term indicates, *composite material* reveals a material that is different from common heterogeneous materials. Currently composite materials refer to materials having strong fibers—continuous or non-continuous surrounded by a weaker matrix material. The matrix serves to distribute the fibers and also to transmit the load to the fibers [Gay,2003]. The composite material as obtained is very heterogeneous and very "anisotropic." This notion of "anisotropy" simply means that the mechanical properties of the material depend on the direction [Jones,1999]. The bonding between fibers and matrix is created during the manufacturing phase of the composite material. This has fundamental influence on the mechanical properties of the composite. Fibers are required to be as thin as possible because their rupture strength decreases as their diameter increases, and very small fiber diameters allow for effective radius of curvature in fiber bending to be on the order of half a millimeter. The assembly of fibers to make fiber forms for the fabrication of composite material can take one of the following forms:

1. Unidimensional: unidirectional tows, yarns, or tapes.
2. Bidimensional: woven or nonwoven fabrics (felts or mats).
3. Tridimensional: fabrics (sometimes called multidimensional fabrics) with fibers oriented along many directions.

Before the formation of the reinforcements, the fibers are subjected to a surface treatment to
1. Decrease the abrasion action of fibers when passing through the forming machines.
2. Improve the adhesion with the matrix material.

2. ANALYTICAL TORSIONAL ANALYSIS OF A FRC BEAM:

Torsion is an important factor in the design of some load carrying elements such as shafts, curved beams, edge beams in buildings, and eccentrically loaded bridge girders. Therefore, the uniform (St. Venant) and non-uniform torsion problem of structural components has long been the subject of theoretical and practical interest in the field of solid mechanics [P.K.,2010 & Terry,2003]. When the torsion of composite materials is studied, they will be assumed to be made of isotropic phases. Macro mechanically, they are assumed to be transversely isotropic [Gay,2003], which is a certain particular case of the orthotropy [Jones,1999]. As shown in Fig.1, 0 is the elastic center, x,y, and z are the principal axes. The beam is slender and uniformly twisted, this means that every cross section is subjected to a pure and constant torsion moment, along the x axis, denoted as Mx. Then, under the application of this moment, each line in the beam, initially parallel to the x axis, becomes a helicoid curve, including (in the absence of symmetry in the cross section) the line which, initially, was coinciding with the elastic x axis itself. The only line which remains rectilinear is cutting the plane of all sections at a point which will be called torsion center and denoted as C, with coordinates y_c and z_c in the principal axes as seen in Fig.1 [Gay,2003].

2.1. Torsional Degree of Freedom

By definition, this is the rotation of each section about the x axis, denoted as θx. The torsional moment *Mx* being constant, the angle θx evolves along the *x* axis in such a manner that, for any pair of cross sections spaced with a distance *dx*, one can observe a same increment of rotation $d\theta x$
Then [Gay,2003]:

$$\frac{d\theta_x}{d_x} = constant \tag{1}$$

Here it is not necessary to define the rotation ϴx by means of an integral of displacements. It will be seen that the displacement field associated with this pure rotation of the sections leads to the exact solution of the problem in the elastic domain (at least for the case of uniform warping), consequently the angle of rotation of the sections varies linearly along the longitudinal axis x. As a consequence, we assume a priori the components of the displacement field ux, uy & uz to be written as:

$$\begin{aligned} u_x &= \frac{d\theta_x}{dx} \times \varphi(y,z) \\ u_y &= -(z - z_c)\theta_x \\ u_z &= (y - y_c)\theta_x \end{aligned} \tag{2}$$

where the function denoted as φ(y,z) is a characteristic of the cross section shape and of the materials that constitute the section. This is called the warping function for torsion [Gay,2003]. Which can be defined as a harmonic function, $\varphi(y,z) = w/\theta_x$, expressing the warping of a cylinder undergoing torsion, where the x, y, and z coordinates are chosen so that the axis of torsion lies along the x axis, w is the x component of the displacement, and θ_x is the torsion angle. Also known as warping function [M. Ariff,2008]. With the displacement field in Eq.2 above, the most important nonzero strains are written as:

$$\begin{aligned} \gamma_{xy} &= \frac{d\theta_x}{dx}\left(\frac{\partial\varphi}{\partial y} - (z - z_c)\right) \\ \gamma_{xz} &= \frac{d\theta_x}{dx}\left(\frac{\partial\varphi}{\partial z} + (y - y_c)\right) \end{aligned} \tag{3}$$

The most considered stresses are then the shear stresses τ_{xy} And τ_{xz}. The torsional moment can be deduced by integration over the domain of the straight section as:

$$M_x = \int_D \left(y\,\tau_{xz} - z\,\tau_{xy}\right) ds = \frac{d\theta}{dx}\int_D G_i \left\{ y\left(\frac{\partial\varphi}{\partial z} - y_c\right) - z\left(\frac{\partial\varphi}{\partial y} + z_c\right) + y^2 + z^2 \right\} ds \tag{4}$$

2.2 Determination of Equivalent Stiffness in Torsion:

There is the parameter of the equivalent stiffness in torsion which can be determined by introducing the function of Φ(y,z) such that [Gay,2003]:

$$\Phi(y,z) = \varphi(y,z) + yz_c - zy_c \tag{5}$$

Substituting Eq.5 in Eq.4 and simplifying, it becomes:

$$M_x = \frac{d\theta_x}{dx}\int_D G_i \left(y\frac{\partial\Phi}{\partial z} - z\frac{\partial\Phi}{\partial y} + y^2 + z^2 \right) ds \tag{6}$$

Thus, the equivalent stiffness in torsion of a composite material can be put in the form of:

$$M_x = (GJ)\frac{\partial\theta_x}{\partial x} \tag{7}$$

3. ASSUMPTIONS:

The following assumptions are adopted for both of fibers and matrix while a static torsional analysis of a unidirectional fiber-reinforced composite cantilever beam is made assuming that [Chen, et. al.,2001 & McGraw-Hill Dictionary, 2003]:

1- The longitudinal stress in the fibers varies linearly across its width while the transverse stress is uniform across the fiber.
2- Perfect bonding between fibers and matrix is assumed to be existed.
3- Fibers and matrix are assumed isotropic, homogeneous and linearly elastic
4- No voids, inclusions, impurities or manufacturing defects and deficiencies are assumed to be involved in beam material.
5- The composite material is considered homogeneous on macroscopic level.
6- The loads are assumed to be applied at the infinity (for the sake of the problem of contact stresses to be turned away).
7- Initially stress-free.
8. The composite material is transversely isotropic [Jones,199 & McGraw-Hill Dictionary, 2003].
9. Torques are uniform and static.

4. DETERMINATION OF EFFECTIVE ELASTIC PROPERTIES:

The constituents of the composite materials considered in this research are chosen from the following fibers: 1. E-Glass 2. Kevlar-49 3. Kevlar-29 4. Carbon fibers (T300).
The matrices are chosen to be: 1. Polyester 2. Polypropylene 3. Epoxy 4. Polyamide.
Each of the fibers above will be taken with each of the matrices mentioned afterwards to constitute a particular composite material, thus sixteen different modular ratios will be gotten. It's arbitrarily chosen to start with Kevlar-49 with the four matrices above at a fiber volume fraction of (V_f =40%) which is experienced as an optimum one from both stiffness and economic considerations [Shaguang Li,1999]. The effective elastic properties of the constituents and the composites with the various values of the modular ratios (G_f/G_m) are as shown in tables-1 through -5 in appendix-1 [Office of Aviation,1997]. The effective properties of the composite materials considered in this research are determined using the well-known rules of mixtures and the Halpin-Tsai Eq. [Shaguang Li,1999]:

$$E_1 = E_f V_f + E_m V_m \tag{8}$$

$$E_2 = \frac{E_f E_m}{E_f V_m + E_m V_f} \tag{9}$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m \tag{10}$$

Where $V_m = 1- V_f$

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f} \tag{11}$$

While ν_{23} can be found through Halpin-Tsai equation stated as:

$$\frac{M}{M_m} = \frac{1+\xi\eta V_f}{1-\eta V_f} \tag{12}$$

Where, E_1: modulus of elasticity of the composite in the longitudinal direction (direction of the fibers).

E_2: modulus of elasticity of the composite in the transverse direction (in a direction normal to that of fibers), equal to E3 in case of transverse isotropy in 2-3 direction.
ν_{ij}: Poisson's ratio of the composite giving the transverse strain in j- direction due to longitudinal strain in i-direction.
G_{ij}: shear modulus of the composite material in i-j plane.
E_f: fibers modulus of elasticity.
E_m: matrix modulus of elasticity.
V_f: fiber volume fraction.
ν_f: Poisson's ratio of the fibers.
ν_m: Poisson's ratio of the matrix.
G_i: shear modulus of the component i.
M: composite modulus (E_2, G_{12} or ν_{23})
M_m: corresponding matrix modulus.
η: reduced factor whose value ≤ 1 and affected by the constituent materials properties as well as by the factor ξ.
ξ: is a measure of the fiber reinforcement of the composite depends on the fiber geometry, packing geometry and loading conditions. An empirical formula found by Hewitt and Malherbe to find (ξ) such that:

$$\xi = 1+40*(V_f)^{10} \tag{13}$$

Thus for $V_f = 40\%$, $\xi = 1$
The factor η can be calculated through the following relation [Gay,2003]:

$$\eta = \frac{\frac{M_f}{M_m}-1}{\frac{M_f}{M_m}+\xi} \tag{14}$$

Since, ν_{23} has already been found therefore G_{23} can be determined using the relation of [Jones,1999]:

$$G_{23} = \frac{E_2}{2(1+\nu_{23})} \tag{15}$$

Thus, the required effective elastic properties of the composite are all found, keeping in mind that it can neither precisely predict the composite module, nor is there any need to. Approximations such as the Halpin-Tsai equations should satisfy all practical requirements. The elastic properties of the constituent materials of the beam under consideration are as given in appendix-1. The major Poisson's ratios ν_{12} and ν_{13} in the cases under consideration are equal due to the transverse isotropy existed in the system idealization adopted in the current study in 2-3 plane [Gay,2003].

5. RESULTS AND DISCUSSION:

It is clearly seen from the results obtained that the elastic behavior of the unidirectional fiber reinforced composite rods under the torsional loading is more highly affected by the matrix shear modulus of rigidity (G_m) than by that of fibers (G_f). In order to check which one, the fiber or matrix having the more dominant effect on the composite properties and behavior under the case of loading of interest, Fig.2 shows the variation of the composite transverse modulus of rigidity G_{23} against that of matrix (G_m), while Fig.3 shows the variation of G_{23}

against that of fiber (G_f). It can be easily seen through the graphical representations and the second degree polynomial equations of the curves displayed on them with the data obtained that the rate of change of G_{23} in case of matrix variation is higher than that when fiber is changed to produce a particular composite material. Mathematically, this means that the first derivatives of the curves equations already mentioned above are of higher values in case of matrix variation. The equations in case of matrix variation with the same fiber are as follows:

$y = -0.2116x^2 + 2.5018x - 0.0886$ for E-glass (fiber variation) (16)
$y = -0.0033x^2 + 0.1645x + 1.4265$ for polyamide (matrix variation)
$y = -0.0002x^2 + 0.0429x + 1.4239$ for polyester (matrix variation)
$y = -0.3035x^2 + 1.2838x + 0.3244$ for Kevlar 29 (fiber variation)

Where y: represents the composite transverse modulus of rigidity G_{23}.
x: represents the matrix shear modulus of rigidity (G_m).
The little deviation noticed between the curves obtained by numerical solution and those resulted by polynomial fit is normal, and could be attributed to assumptions and approximations made by the numerical solution.
Therefore, the angle of twist θ_z was of higher values and at highly varying rate of change when the composite differed according to matrix material Fig.4. When the composite variation is being done on the basis of fibers changing, the variation of the angle of twist will take the behavior shown in Fig.7 whose values are more convergent. These results can be physically interpreted as the torsional load is applied on the external layers of the rod where the majority of it, is primarily met by the matrix material, afterwards the load transferred to the fibers buried inside the matrix so it carries a small share of it. Secondly, it may be due to the direction of fibers (laid parallel to rod axis and perpendicular to plane of applied torsion) so, there is no sufficiently large resistance can be developed by fibers to torsion load. For the purpose of verification of the results obtained, analytical values of the angle of twist for the same configuration and loading conditions considered are compared with values numerically obtained from the software of ANSYS v12, showing the same behavior with a ratio of convergence about 80% or more in most cases for the angle of twist Figs.5&8. Perfect conformity between analytical and numerical values of shear stresses which are unaffected by the materials changing as it is a function of both of the magnitude of the applied torsion and the geometry of the cross-section in all cases as shown in Figs.6 & 10.

6. CONCLUSIONS:

The following conclusions can be drawn from the results obtained:

1. Under the torsional loading of the fiber reinforced composite materials, it should be taken care of the choice of the matrix more than the fiber.

2. The angle of twist of the composite rod is more affected by matrix than by fiber.

3. Shear stresses induced are unaffected by the variation of matrix or the fibers.
4. The increase of the angle of twist is directely proportional to G_f/G_m.

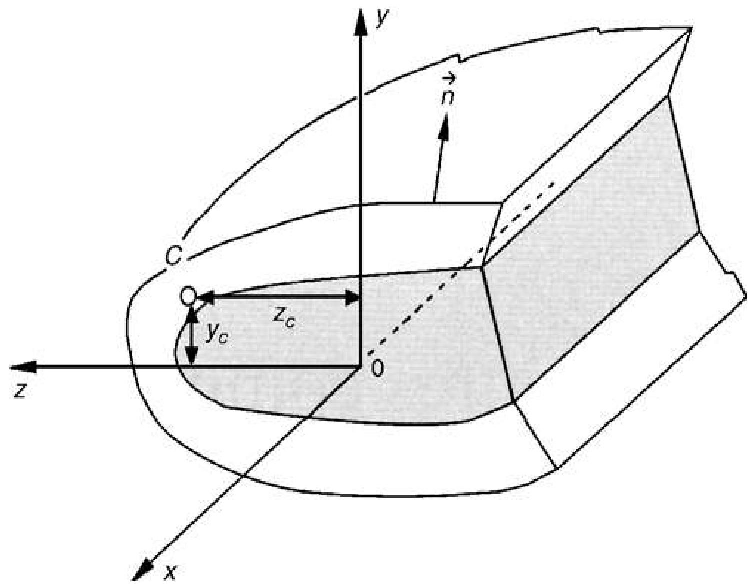

Figure 1: Elastic Center (O), Torsion Center (C), and Principal Axes (x, y & z) of the rod.

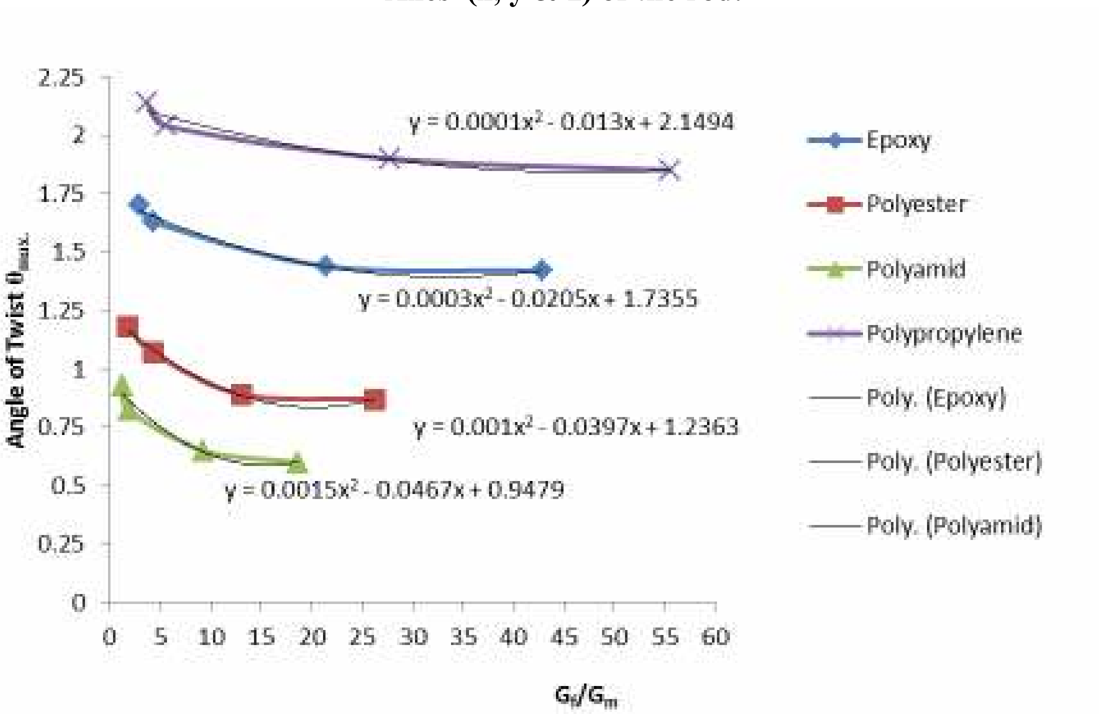

Fig.2: Effect of G_f/G_m on the angle of twist ($\theta_{max.}$) in case of matrix changing for the same fibers group.

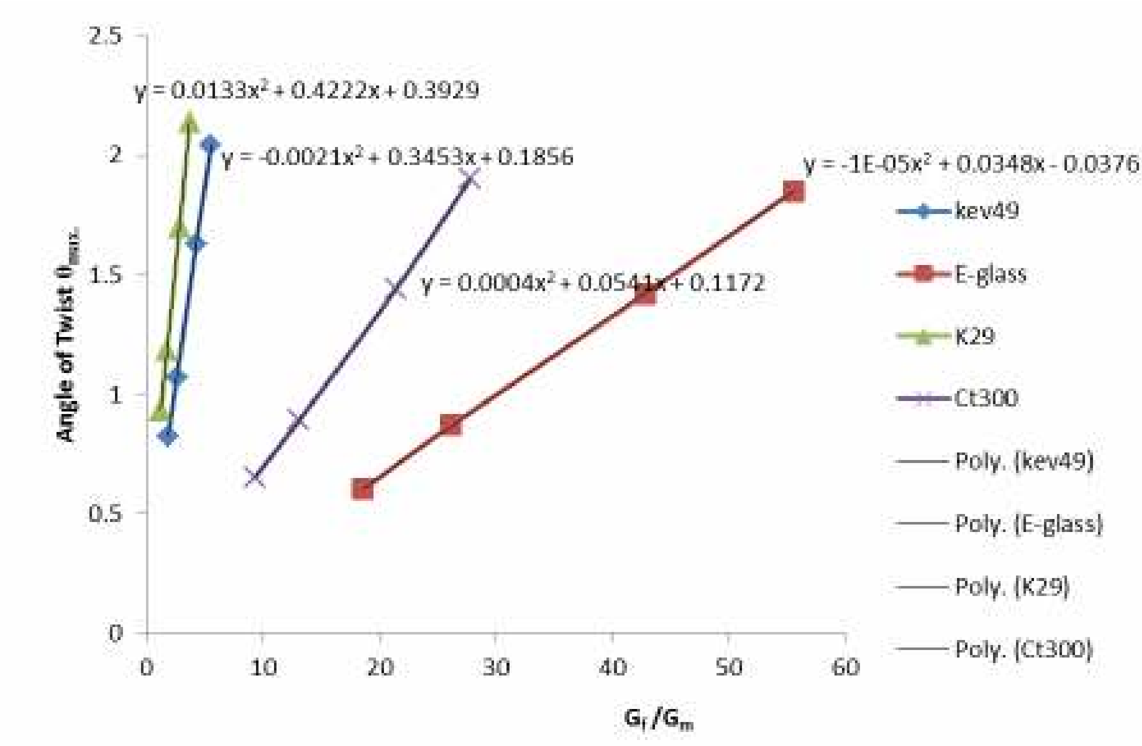

Fig.3: Effect of G_f/G_m on the angle of twist ($\theta_{max.}$) in case of fibers changing for the same group of matrices.

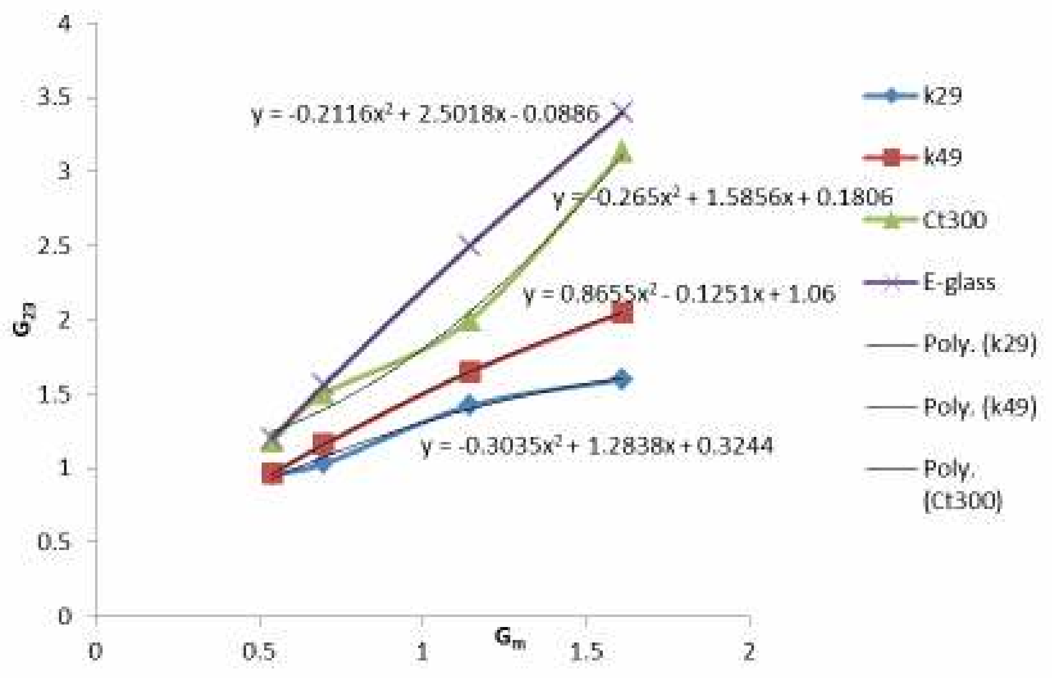

Fig. 4: Effect of matrix shear modulus (G_m) on composite transverse shear modulus (G_{23})

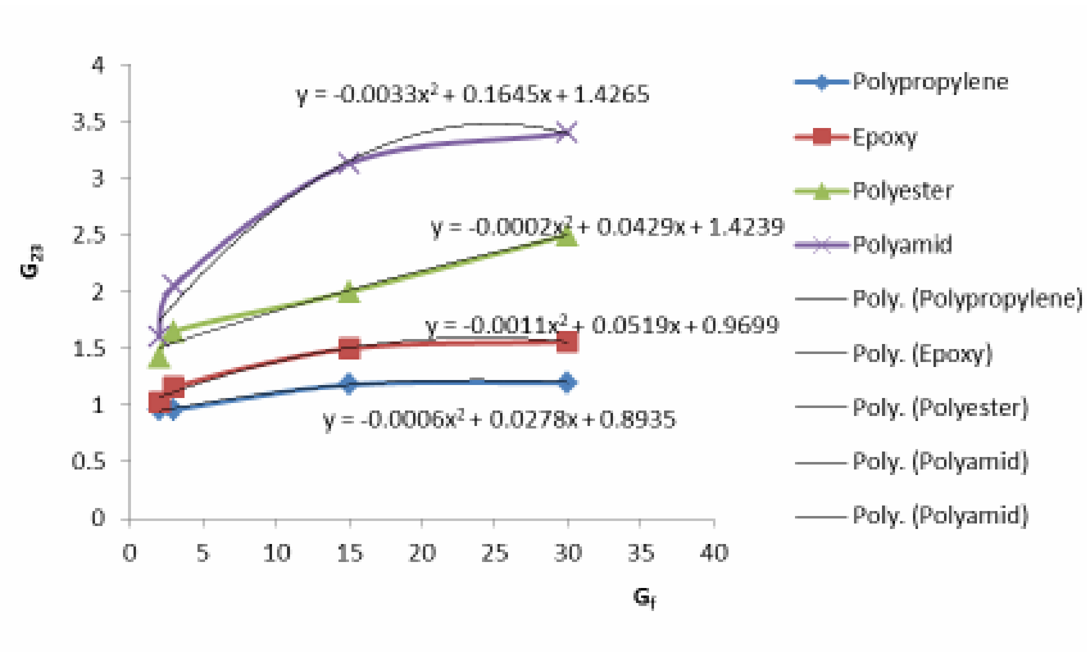

Fig.5: Effect of fiber shear modulus (G_f) on composite transverse shear modulus (G_{23})

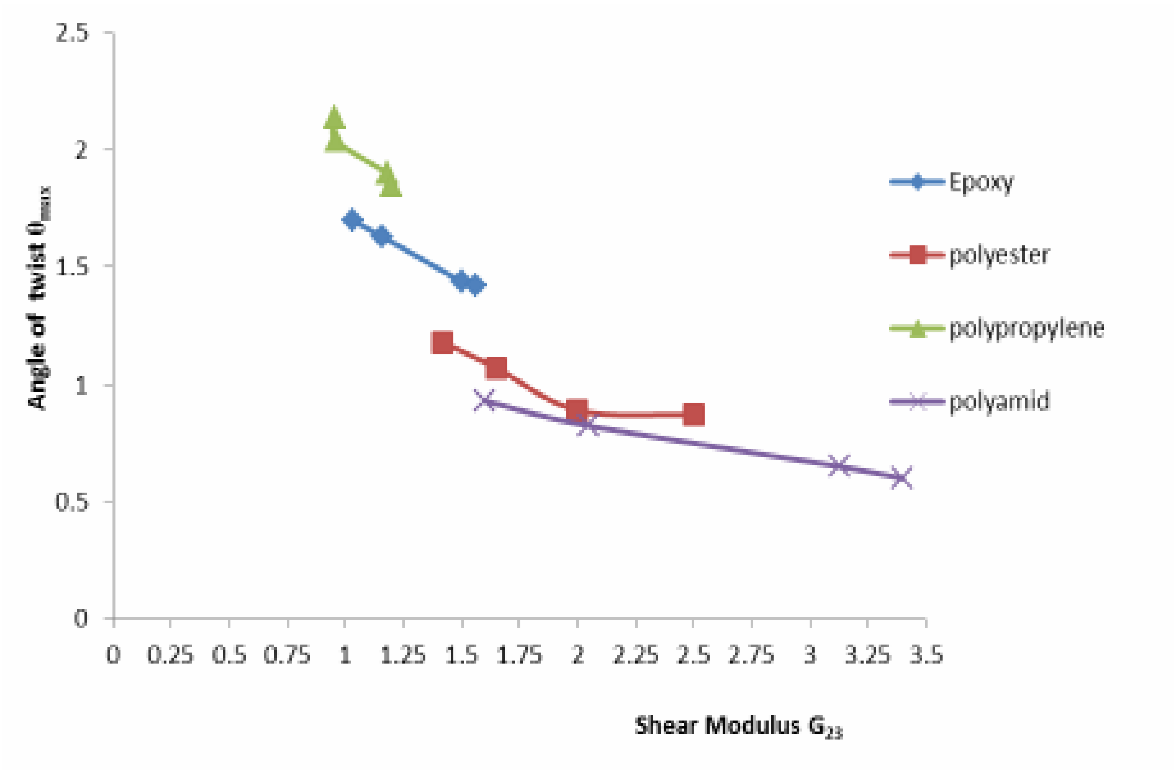

Fig. 6: Effect of matrix on angle of twist for the same group of fibers (numerical solution).

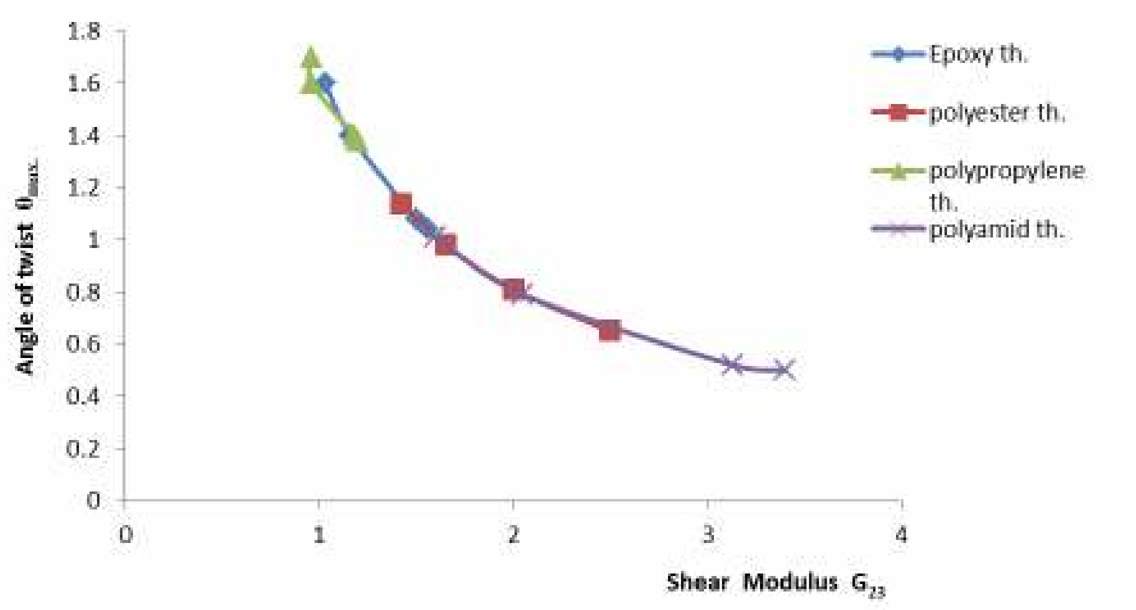

Fig. 7: Theoretical (analytical) values of twist angle with various matrices and the same group of fibers.

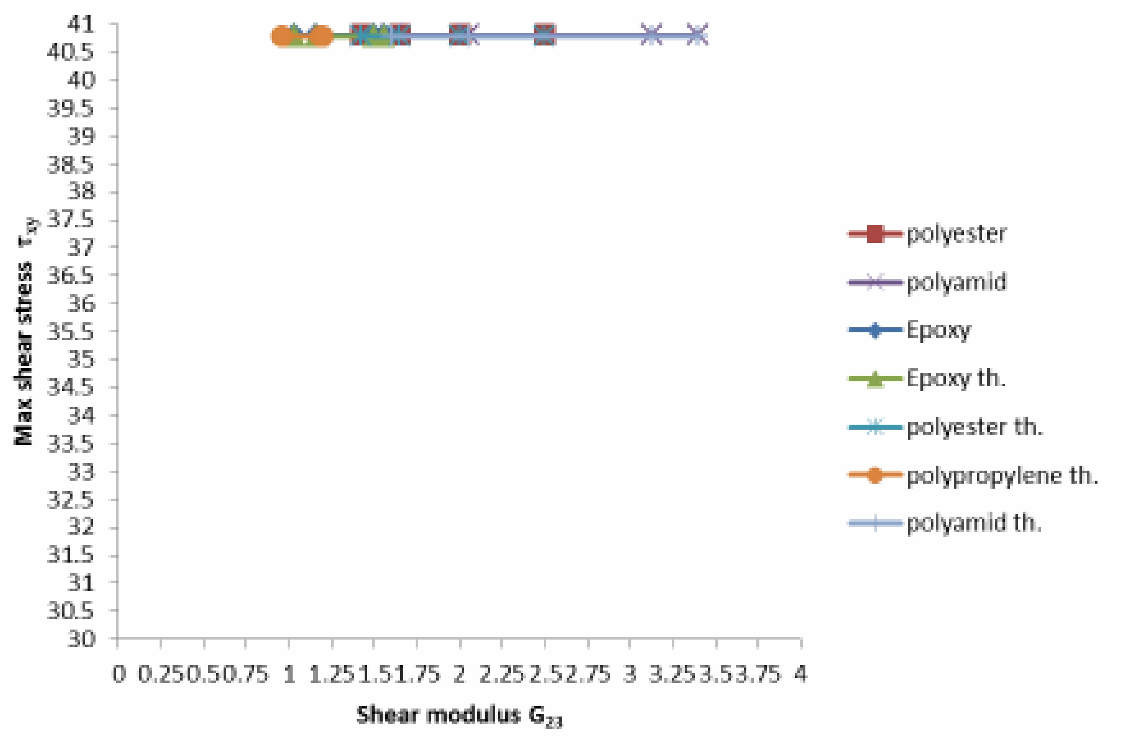

Fig. 8: Max. shear stress τ_{xy} induced in the rod under different matrices for the same fibers compared with their analytical values.

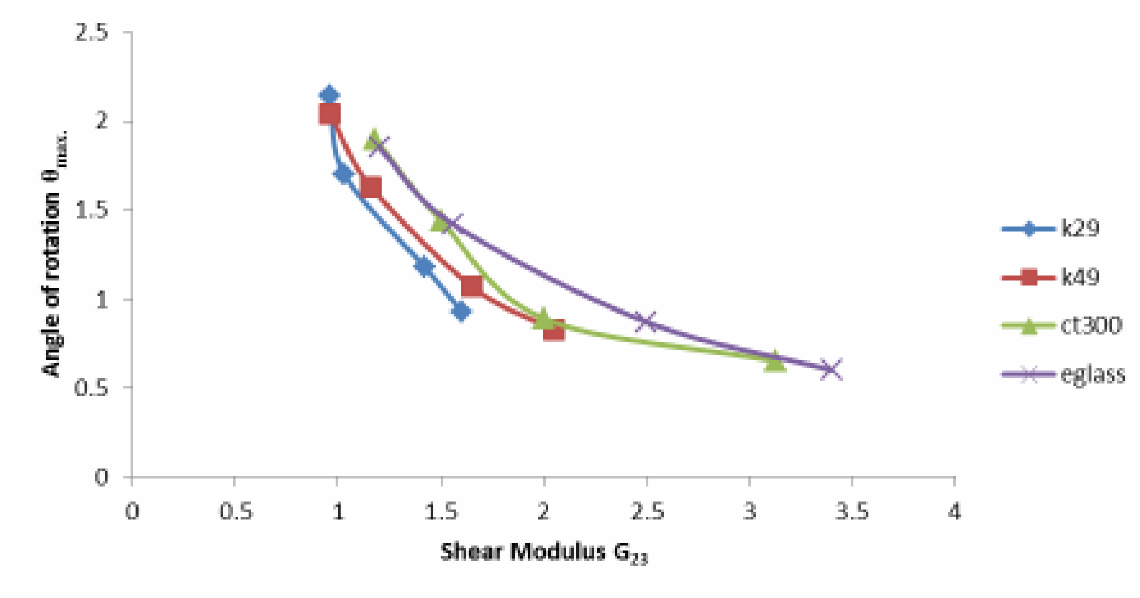

Fig. 9: Effect of fibers on angle of twist for the same group of matrices (numerical solution).

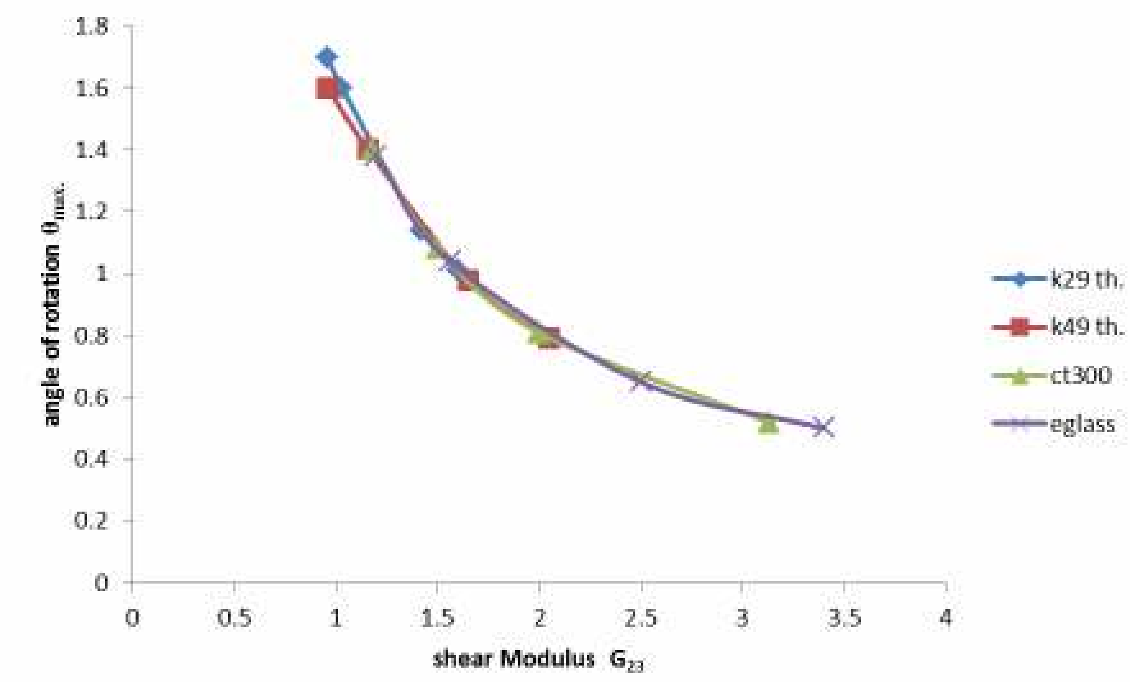

Fig.10: Effect of fibers on angle of twist for the same group of matrices (analytical solution).

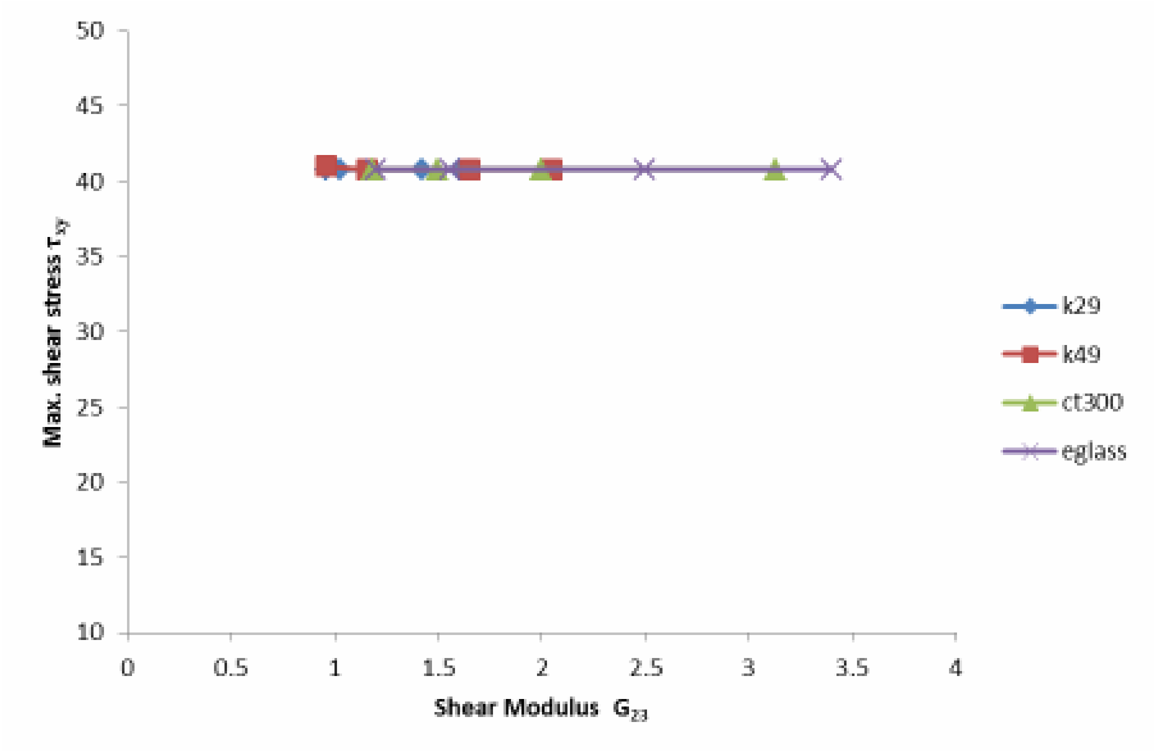

Fig. 11: Max. shear stress τ_{xy} induced in the rod under different matrices for the same fibers (numerical solution).

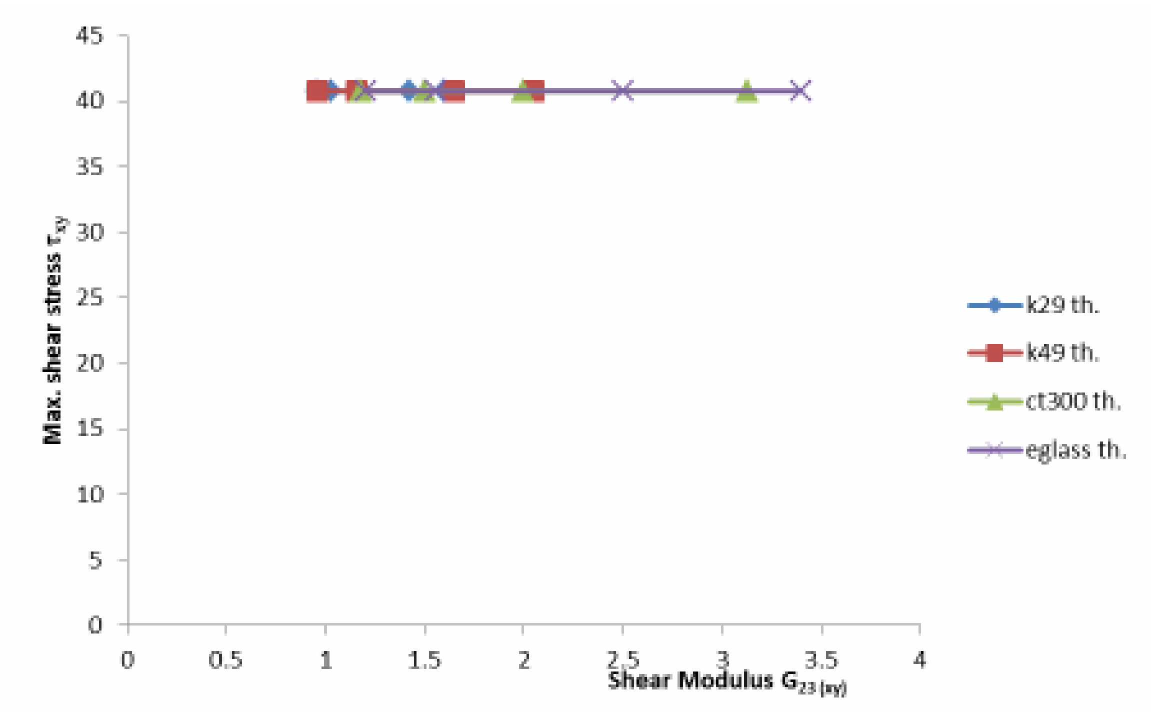

Fig. 12: max. shear stress τ_{xy} induced in the rod under different matrices for the same fibers (analytical solution).

Table-1: Elastic properties of the Matrices [10]:

No.	Type of Matrix	E_m(GPa)	G_m(GPa)	ν_m
1	Epoxy	1.7	0.7	0.27
2	Polyester	2.75	1.146	0.2
3	Polypropylene	1.3	0.54	0.22
4	Polyamide	4.2	1.615	0.3

Table-2: Elastic properties of the Fibers [10]:

No.	Type of Fiber	E_f(GPa)	G_f(GPa)	ν_f
1	. Kevlar-49	125	3	0.35
2	E-Glass	81.4	30	0.22
3	. Kevlar-29	93	2	0.35
4	Carbon Fibers T300	230	15	0.3

Table-3: Values of modular ratio (G_f/G_m) of the composites considered

Matrices / Fibers	Epoxy	Polyester	Polypropylene	Polyamide
Kevlar-49	4.28	2.62	5.56	1.86
E-Glass	42.86	26.2	55.56	18.6
Kevlar-29	2.86	1.74	3.7	1.24
Carbon Fibers T300	21.43	13.1	27.8	9.3

Table-4: Effective elastic properties of the four fibers/Epoxy

Fiber Type	E_1(GPa)	E_2(GPa)	$\nu_{12}=\nu_{13}$	G_{12}(GPa)= G_{13}	ν_{23}	G_{23}(GPa)
Kevlar-49	51.02	2.81	0.302	1	0.29	1.1
E-Glass	33.58	2.79	0.25	1.15	0.25	1.8
Kevlar-29	38.22	2.8	0.302	0.964	0.29	0.83
Carbon Fibers T300	93.02	2.82	0.282	1.2	0.27	2.7

Table-5: Effective elastic properties of the four fibers/ Polyester

Fiber Type	E_1(GPa)	E_2(GPa)	$\nu_{12}=\nu_{13}$	G_{12}(GPa)= G_{13}	ν_{23}	G_{23}(GPa)
Kevlar-49	51.65	4.51	0.26	1.522	0.25	1.65
E-Glass	34.21	4.48	0.208	1.86	0.2	2.5
Kevlar-29	38.85	4.49	0.26	1.38	0.25	1.42
Carbon Fibers T300	93.65	4.55	0.24	1.82	0.23	2

Table-6: Effective elastic properties of the four fibers/ Polypropylene

Fiber Type	E_1(GPa)	E_2(GPa)	$\nu_{12}=\nu_{13}$	G_{12}(GPa)= G_{13}	ν_{23}	G_{23}(GPa)
Kevlar-49	50.78	2.1517	0.272	0.8	0.26	0.96
E-Glass	33.34	2.144	0.22	0.88	0.22	1.2
Kevlar-29	37.98	2.146	0.272	0.762	0.26	0.957
Carbon Fibers T300	92.78	2.16	0.252	0.88	0.25	1.18

Table-7: Effective elastic properties of the four fibers/ Polyamid

Fiber Type	E_1(GPa)	E_2(GPa)	$\nu_{12}=\nu_{13}$	G_{12}(GPa)= G_{13}	ν_{23}	G_{23}(GPa)
Kevlar-49	52.52	9.99	0.32	1.98	0.32	2.055
E-Glass	35.08	9.746	0.268	2.6	0.26	3.4
Kevlar-29	39.72	9.83	0.32	1.75	0.32	1.6
Carbon Fibers T300	94.52	10.22	0.3	2.5	0.3	3.13

Table-8: Angles of twisting (rotation)(θ) and shear stresses of the four fibers/Epoxy

G23	$\theta_{max.\ Rad}$	$\tau_{max.MN/m^2}$	4 fibers/epoxy	$\theta_{max.\ Th.\ rad}$	$\tau_{max.th\ MN/m^2}$
1.03	1.7	40.8	kevlar-29	1.6	40.78
1.16	1.63	40.8	kevlar-49	1.4	40.78
1.5	1.44	40.8	Carbon T300	1.08	40.78
1.56	1.42	40.8	E-glass	1.04	40.78

Table-9: Angles of twisting (rotation)(θ) and shear stresses of the four fibers/ polyester

G23	$\theta_{max.\ Rad}$	$\tau_{max.MN/m^2}$	4 fibers/polyester	$\theta_{max.\ Th.\ rad}$	$\tau_{max.th\ MN/m^2}$
1.42	1.18	40.8	kev29	1.14	40.78
1.65	1.07	40.8	kevlar-49	0.98	40.78
2	0.89	40.8	Ct300	0.81	40.78
2.5	0.87	40.8	E-glass	0.65	40.78

Table-10: Angles of twisting (rotation)(θ) and shear stresses of the four fibers/ polypropylene

G23	$\theta_{max.\ Rad}$	$\tau_{max.MN/m^2}$	4fibers/polypropylene	$\theta_{max.\ Th.\ rad}$	$\tau_{max.th\ MN/m^2}$
0.957	2.14	40.8	k29	1.7	40.78
0.96	2.04	41	k49	1.6	40.78
1.18	1.9	40.8	ct300	1.4	40.78
1.2	1.85	40.8	E-glass	1.38	40.78

Table-11: Angles of twisting (rotation)(θ) and shear stresses of the four fibers/ polyamid

G23	$\theta_{max.\ Rad}$	$\tau_{max.MN/m^2}$	4 fibers/polyamid	$\theta_{max.\ Th.\ rad}$	$\tau_{max.th\ MN/m^2}$
1.6	0.93	40.8	k29	1.01	40.78
2.05	0.824	40.8	k49	0.79	40.78
3.13	0.65	40.8	ct300	0.52	40.78
3.4	0.6	40.8	E-glass	0.5	40.78

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