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Technical Notes

THE EFFECTED PARAMETERS FOR DESIGNING THE SINGLE LAYER COMPOSITE MATERIALS

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In this work the mathematical software was used to present the simple mechanical behavior of a single layer of composite material. The effect of volume fraction of continuous fibre, loading angles and orientation of fibres distribution in the matrix was investigated. It was shown that the strength has been increased as the fibre volume fraction increases. Similar results were obtained for the composites that using the E-glass and S-glass fibre. The maximum exhibited modulus of elasticity was obtained when the fibr's angle is equal to the loading angle. The virtual design points have been determined for both types of glass. Therefore, the optimum working limits were determined. The results indicate that the S-glass gives ranges of properties to work higher than E-glass. Moreover, the results show that these ranges of working properties will be decreased as the volume of fraction decreases.

Keywords: Composite materials, Fibre angle, Loading angle, Modulus of composite, Mechanical properties, Volume of fraction

INTRODUCTION

The purposes from the construction of composite materials are to create a strong, stiff and light material. Materials such as glass, carbon and kevlar have extremely high tensile and compressive strength (Talib *et al.*, 2011). These materials are brittle, therefore, in solid form many random surface flaws present in such materials. These flaws can be propagated when subjected to the stresses and then the materials will fail according to the fracture mechanics theory.

Design parameters of the fibre-reinforced composite materials having the required effective stiffness and strength properties are presented. Different averaging techniques have been adopted to estimate the effective elastic properties of composites. Analytical averaging schemes were also utilized by other studies (Milton and Kohn, 1988; Christensen,

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1990; Chou, 1992; Nasser and Hori, 1993; Vinson, 1993; Reddy and Robbins, 1994; and Kalamkarov and Kolpakov, 1996) to provide an estimate of the overall elastic properties of inhomogeneous composite structures.

Fibre Reinforced Plastics or Polymers (FRP) are a general term for composite materials that consist of a resin matrix. This matrix contains reinforcing fibres such as glasses which have a greater strength or stiffness than the resin. Reinforcing fibres can be made of metals, ceramics, glasses, or polymers that have been turned into graphite and known as carbon fibre. Fibres increase the stiffness of the matrix material. The strong covalent bond along the fibre length gives them a very high stiffness in this direction because the bonding force between the immersed fibers and the matrix. In other hand, the process for making the fiber in the composite might be still relatively expensive and need technical awareness.

Epoxies materials are widely used for airframe structures with limit 120 °C (250 F°) with decades of successful flight experience (Zweben, 2000). These materials tend to be rather brittle materials. But they are toughened formulations with greatly improved impact resistance are available (Gu *et al.*, 2000).

This work is focused on reinforced composites with continuous fibres since they are the most efficient structural materials. The software package that covers simple mechanics concepts of stiffness and strength has been used. This software can be applied to all composites.

Most composite materials have strong, stiff fibres in a matrix which is weaker and less stiff. The objective is usually to make a component which is strong and stiff, often with a low density. Commercial material commonly uses glass or carbon fibres in matrix based on thermosetting polymers, such as Epoxy or polyester resins. Furthermore, the adding of the fibre or, in some cases, particles are to improve creep, wear, fracture toughness, and thermal stability.

The performance of fibre-reinforced composites is often controlled by the properties of the fibre-matrix interface (Gu *et al.*, 2000). Good interfacial bonding (or adhesion) is a primary requirement to ensure load transfer from the matrix to reinforcement fiber. The maximum strength and properties can be obtained in the direction of fiber alignments (William and Callister, 2007). The optimum design points have been determined for both types of glass.

CHOOSING THE FIBRE

Three types of fibers have considered today for most composite structures namely; glass (E- and S-glass); Kevlar and carbon or graphite. Nevertheless, other fibers such as boron, spectra, quartz, and ceramics are available. But, these fibres are usually reserved for specialized application. Table 1 shows the advantages and disadvantages of some fiber types.

Glass Fiber

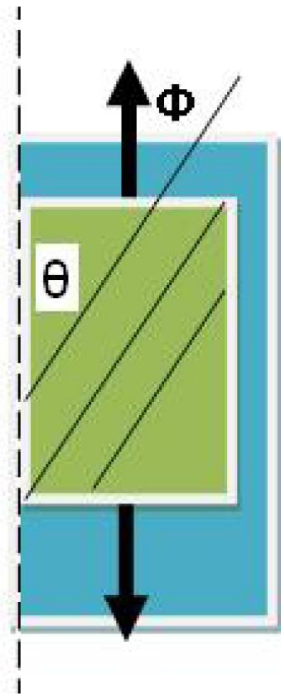
Fiber glass is the most widely used composite material in polyester resin. This material is commonly referred to as just fiberglass. Fiberglass is light weight, corrosion resistant, economical, and easily processed. This type is the most widely used due to the combination in properties between polymer and glass. The instruments and parts which need the

Table 1: Fibre Types

Fiber	Advantages	Disadvantage
E-, S-Glass	High strength	Low stiffness
	Low cost	Short fatigue life high temp. sensitivity
Aramid (Kevair)	High tensile strength	Low compression strength
Boron	Low density	High moisture absorbs
	High stiffness, and high compression strength	High cost
Carbon (AS4, T300)	High strength, and high stiffness	Moderate cost
Graphite (Pitch)	Very high stiffness	Low strength, High cost
Ceramic (Silicon Carbide, Alumina)	High stiffness, and high use temp.	Low strength, High cost

corrosion resistance, strength and light weight are the examples of fiber glass composite material. Glass fibers are made of silicon oxide in addition to the small amounts of other oxides, see Figure 1.

Figure 1: (a) Glass Fiber Orientation, Loading and Fiber Angle



There are two main types of glass fibers; E-glass and S-glass. The first type is the most used, and takes its name from its good electrical properties that no electrical interference in thunderstorms and no spark. The second type-S is very strong, stiff, and temperature resistant where the name it taken, see Table 2. Other names are listed in Table 3. For more details see also (Higgins, 2006).

Table 2: Glass Fibre Properties

E-Glass	S-Glass
Softens at approx. 850 °C	Softens at approx. 1000 °C
Most inexpensive fiber	Approx. 30% stronger than E-glass
Most commonly used fiber today	Approx. 15% stiffer than E-glass
Insulators and capacitors	Approx. 3 times as expensive as E-glass
	High quality glass fiber
	High technical purposes

Tables 3 and 4 show the mechanical properties of composite reinforcing fibers and properties of matrix (Lukkassen and Meidell, 2003). Here E is the modulus of elasticity, σ_b is the tensile strength, and ρ is the density (Gerstle, 1991). The addition of glass S- and E-type will improve the materials properties. For more details see also (Higgins, 2006).

Table 3: Properties of Composite Reinforcing Fibers

Materials	E (GPa)	σ_b (GPa)	ε_b (%)	ρ (Mg/m^3)	E/ρ (MJ/Kg)	σ_b/ρ (MJ/Kg)	Cost ($/Kg)
E-Glass	72.4	2.4	2.6	2.54	28.5	0.95	1.1
S-Glass	85.5	4.5	2.0	2.49	34.3	1.8	22-23
Aramid	124	3.6	2.3	1.45	86	2.5	22-33
Boron	400	3.5	1.0	2.45	163	1.43	330-440
HS Graphite	253	4.5	1.1	1.80	140	2.5	66-110
HM Graphite	520	2.4	0.6	1.85	281	1.3	220-660

Source: Lukkassen and Meidell (2003)

Table 4: Properties of Matrix Materials

Materials	Density (GPa)	Young's Modulus E (GPa) (%)	Shear Modulus G (GPa)	Poisson Ratio (ν)	Tensile Strength σ_t (GPa)	Thermal Expansivity α ($\mu\varepsilon K$–1)
Epoxy	1.25	3.5	1.27	0.38	0.04	58
Polyester	1.38	3.0	1.1	0.37	0.04	150
PEEK	1.30	4	1.4	0.37	0.07	45
Polycarbonate	1.15	2.4	0.9	0.33	0.06	70
Polyurethane Rubber	1.2	0.01	0.003	0.46	0.02	200
Aluminum	2.71	69	26	0.33	0.07	24
Magnesium	1.74	45	7.5	0.33	0.19	26
Titanium	4.51	115	44	0.33	0.24	8
Borosilicate Glass	2.23	64	28	0.21	0.09	3.2

Source: Lukkassen and Meidell (2003)

Materials and Modeling

The glass types-E and S are used as a fiber with epoxy matrix materials. The loading angle (Φ) with respect to the fiber pieces axis has a big role, see Figure 1b. Tables 5 and 6 shows the used values of fiber and loading θ and Φ, respectively, see also Figure 1.

Table 5: Fiber Angle Values

Fiber Angle ($\theta°$)	0	30	60	90

Table 6: Loading Angles Values

Loading Angle ($\Phi°$)	0	30	45	60	90

MATTER software (Material Science, 2000) was used to calculate the Young's modulus. Most of the material in this package is based on a recently published book (Hull and Clyne, 1996). It is a mathematical software and calculator developed by Liverpool University (Material Science, 2000).

The variation of young's modulus with loading directions, fiber angle, matrix and fiber materials have been studied using this model.

The volumes of fiber's fractions (f %) and direction of their alignments were chosen from 0-90° according to the loading directions.

Stiffness

The fiber direction, the fiber and matrix phases act in parallel to support the load σ_1 (Roylance, 2000). The strains in the matrix and in the fiber must be the same as long as the two phases are perfectly bonded, see (Bao, 1991). So that the strain in the fiber direction can be written as:

$$\varepsilon_f = \varepsilon_m = \varepsilon_1 \quad ...(1)$$

The forces in each phase must add to balance the total load on the material. Since the forces in each phase are the phase stresses times the area which numerically equal to the volume fraction, the axial stresses in materials are approximated by (Foster, 1998):

$$\sigma_1 = \sigma_f V_f + \sigma_m V_m = E_f \varepsilon_1 V_f + E_m \varepsilon_1 V_m \quad ...(2)$$

The modulus of elasticity relation of fiber is found according to what's known a rule of mixture prediction, see also (Higgins, 2006):

$$E_1 = \frac{\sigma_1}{\varepsilon_1} = V_f E_f + V_m E_m \quad ...(3)$$

If the stress is applied in the direction transverse to the fibers and matrix, the slab model can be applied. In this case the stress on the fiber and matrix are equal distributed. The overall transverse deflection is (see Higgins, 2006):

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad ...(4)$$

RESULTS AND DISCUSSION

The aims of this work being to show the behavior of the composite materials using a simple mathematical model. Therefore, this model is based on the single layer composite materials. The composites consist of epoxy matrix that reinforced with fibers HS glass, and E-glass) because of their excellent mechanical properties, and fatigue strength. Composites have largely replaced metals in fatigue-critical aerospace applications, such as helicopter rotor blades. Composites also are being used in commercial fatigue-critical applications, such as automobile springs (Zweben, 2000). Therefore, the optimum design limits have been proposed in the area between the intersected curves.

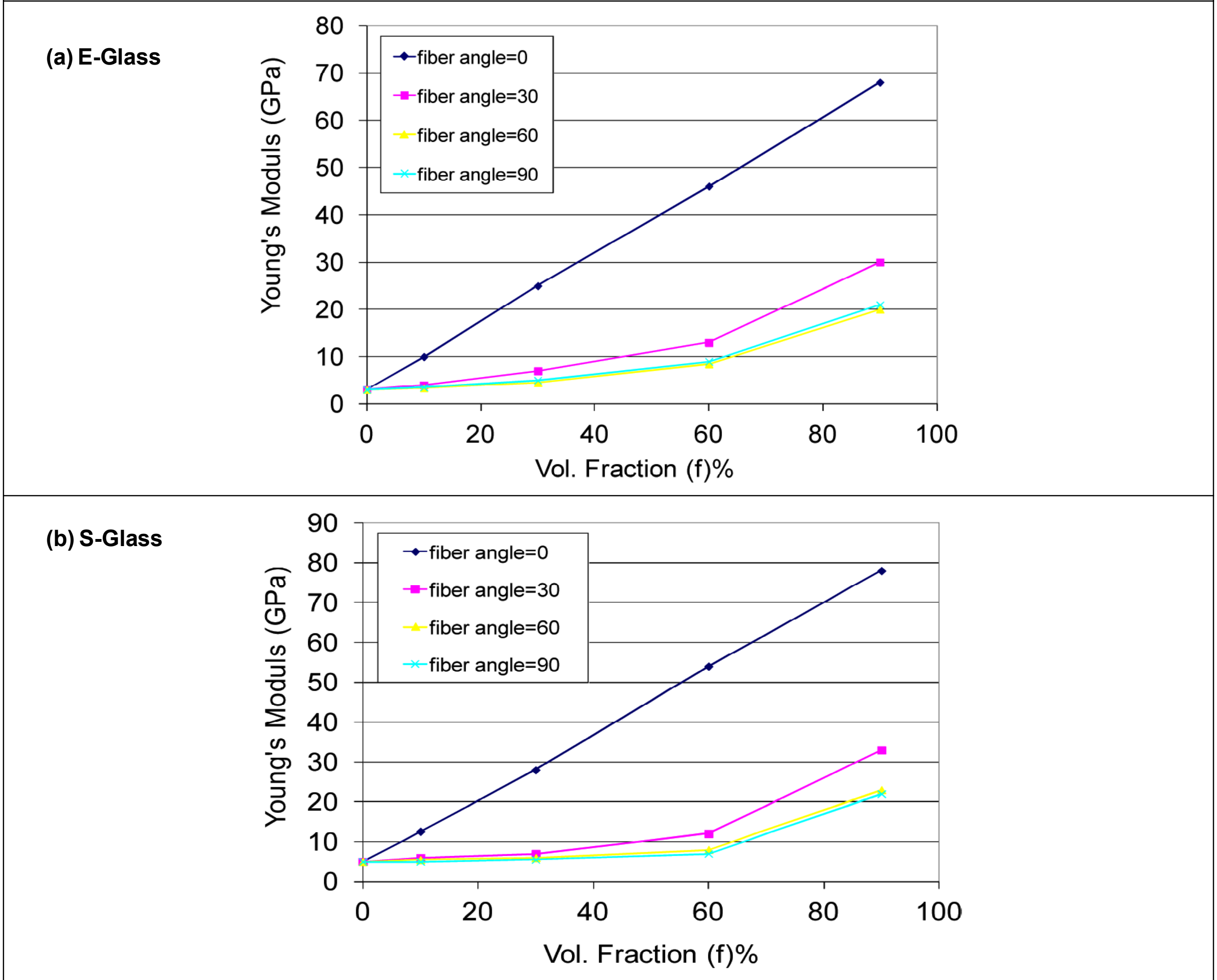
Polymers are relatively weak, low-stiffness materials. Therefore, they have reinforced with continuous or discontinuous fibers for structural application.

The leading types of glass fibers are E-glass and High-Strength (HS) glass. E-glass fibers, the first major composite reinforcement, were originally developed for electrical insulation applications (that is the origin of the E). E-glass is the most widely used of all fibrous reinforcements, because their low cost.

Effect of Volume Fraction of Fiber (f %)

The strength and modulus of elasticity increase as the fiber volume fraction increases as shown in Figures 2 and 3. The rule of mixture prediction provides an upper bound to the composite modulus (parallel load), see Equation (3). In contrast Equation (4) is a lower bound (transverse load), see Figures 2 and 3. The Isostrain (upper bound) is called for the load is parallel to the fiber direction. While Isostress is called for the transverse direction (lower bound).

Figure 2: Effect of Fiber Volume of Fraction and Angle on the Strength of Glass-Epoxy Composite (Φ = 0°)



The value of lower and upper bounds of S-glass is higher than those for E-glass. That because, S-type has the higher properties than E-type. The predicted behavior agrees very well with the description by Gu *et al.* (2000).

Volume fraction of fibers has an effect on the modulus of the matrix material. It can be shown that the variance of young's modulus with respect to the fiber angle of the upper bound (highest stiffness and high strength) to the lower bound (lower stiffness, and lower strength). Most practical cases will be somewhere between these two values. These results agree with that mentioned by Roylance (2000).

The addition of the both types of glass increases the modulus (Zweben, 2000). The highest limits for particle designing show that the S-glass has a range from 77.7 GPa to 21.81 GPa for volume fraction 90% owing to the higher stiffness and strength than for E-glass. For the E-glass have the limit of bound 68.7 GPa to 21.18 GPa at volume fraction

90%. Therefore, more allowance design it must choose than stiffer fiber that give a wide range for particle case design.

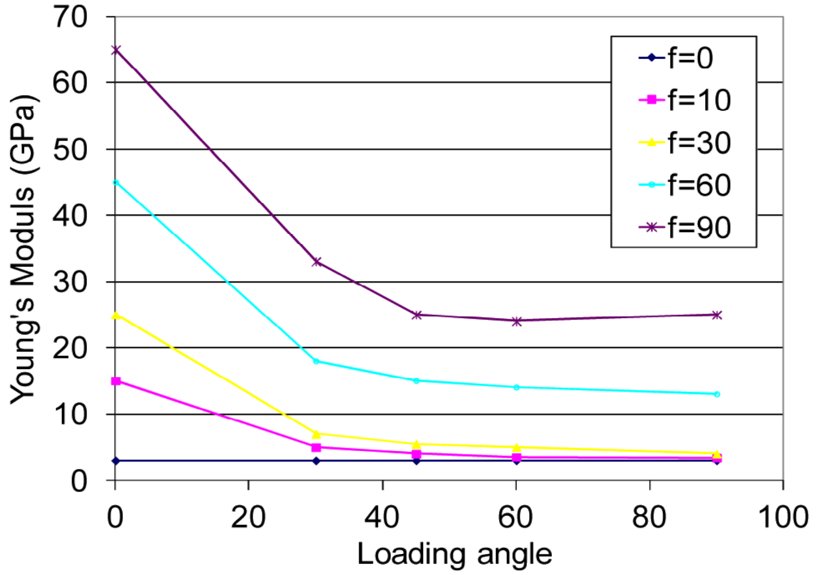
At zero angles, the behavior is fast linear. So that it more suitable for designing the rotor of helicopter blades due to the effect of rotation acceleration. The other angles have nonlinear behavior.

Effect of Loading Angle (Ø) and Fiber Angle (θ)

Figure 3 shows the obtained properties at room temperature made PMC employing an epoxy matrix for the E-glass, and S-glass. The increasing of loading angle decreases the modulus of elasticity. The maximum value of modulus occurs at the loading angle equal to the fiber angle.

Figure 3: Effect of Loading Angle on the Strength of E-Glass

(a) θ = 0



(b) θ = 30

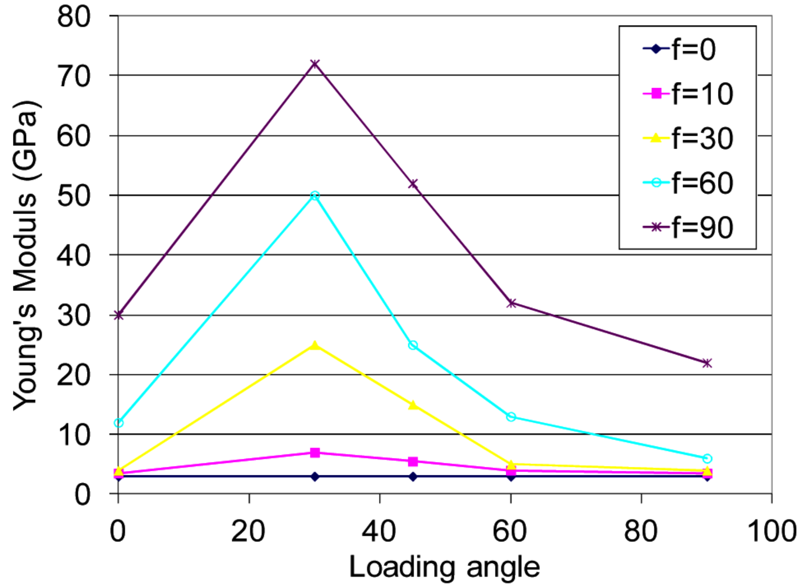
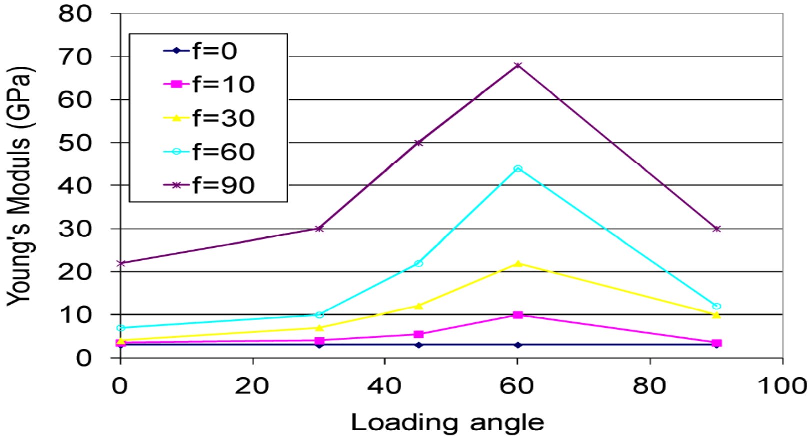
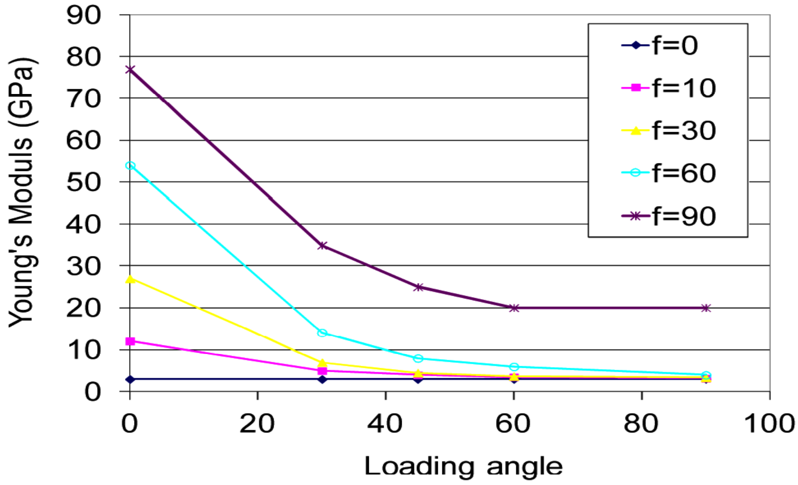


Figure 3 (Cont.)

(c) $\theta = 60$



(d) $\theta = 90$



Similar results were obtained for the S-glass type. Nevertheless, S-glass fibers have has the highest value of modulus due to their properties, as shown in Figure 4.

Figure 4: Effect of Loading Angle on the Strength of S-Glass

(a) $\theta = 30$

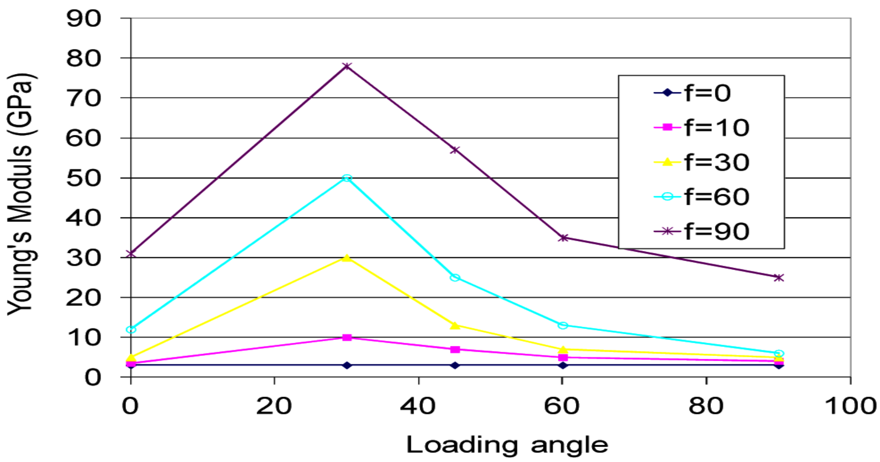
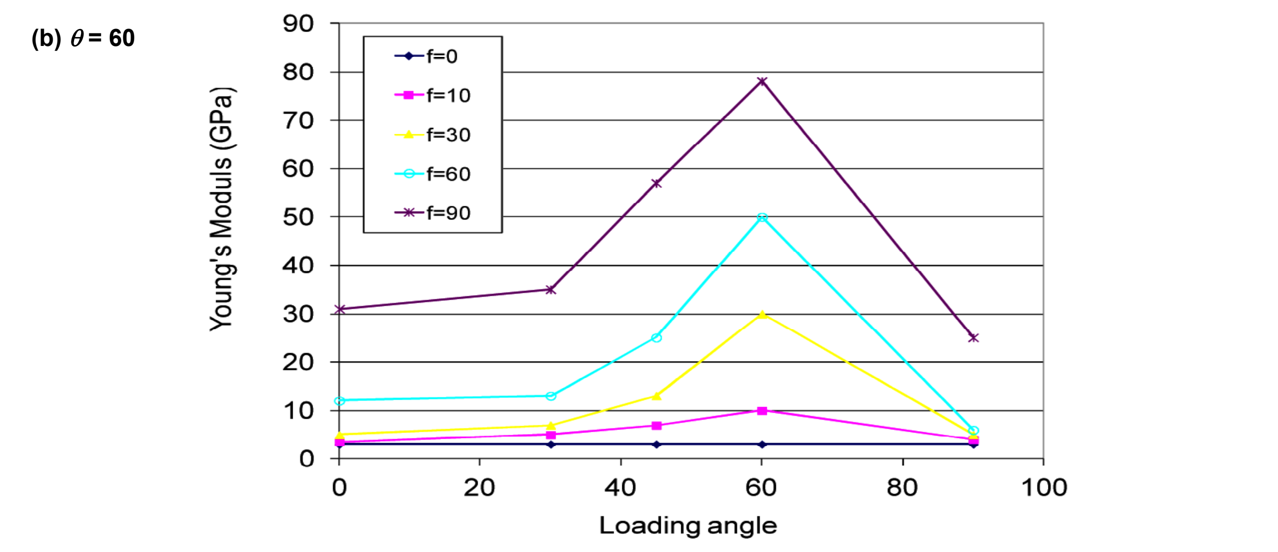


Figure 4 (Cont.)



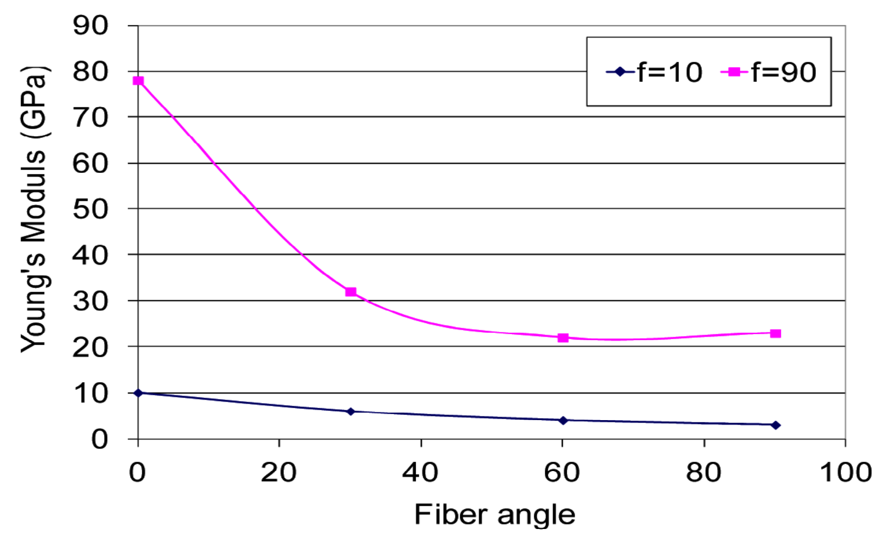
The fibers may be oriented randomly through the material. But it is also possible to arrange them to be oriented preferentially in the direction that expected to have the highest stresses, $\theta = \Phi$, or $\theta = 0$. Such a material is said to be anisotropic (different properties in different directions).

The control of the anisotropy properties is an important means for optimizing the material for specific applications (Roylance, 2000).

The mechanical properties increase when the fibers oriented parallel to the direction of the applied stress. These result agrees well with those stated by Jean (2002).

As the fiber angle increase with constant of volume fraction, the modulus of elasticity will decrease, see Figure 5. The limit will reduce as the fiber angle increases which refers to the decreasing in strength and stiffness.

Figure 5: Variation of the Modulus of Elasticity with Fiber Angle



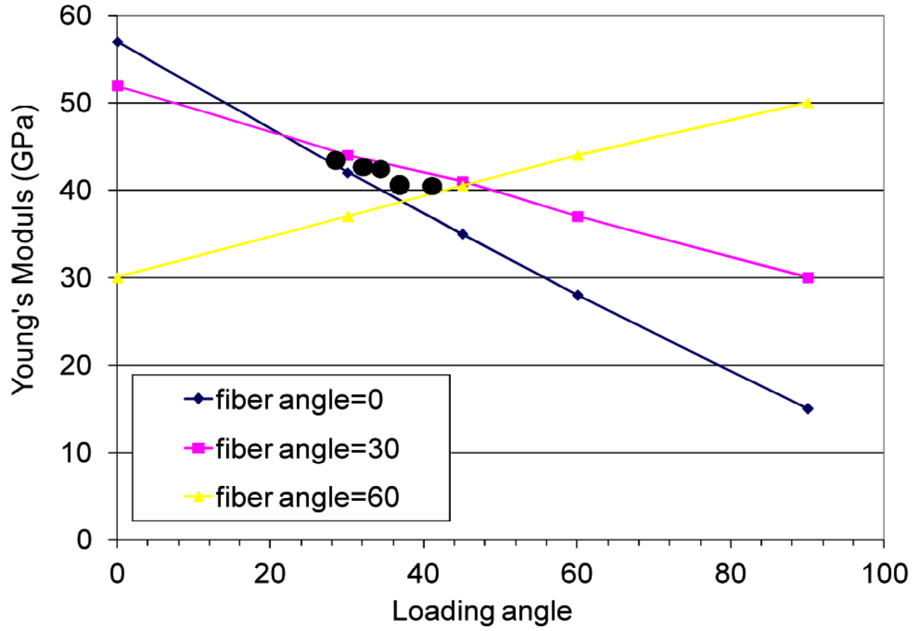
Optimum Design Points and Limits

The optimum design which gives the condition for Epoxy-glass composite material has been determined. The volume of fraction equal to 90% will give higher strength, see Figure 6.

By decreasing to 60%, the optimum limits will decrease and a smaller limit of condition will be obtained as shown in Figure 6. Up to f equal to 30% the limit will reach to 11-13 (GPa), see Figure 6c. The S-glass give a wide range for practical design conditions, see Figure 7.

Figure 6: Optimum Design Points for E-Glass Type

(a) *f* = 90%



(b) *f* = 60%

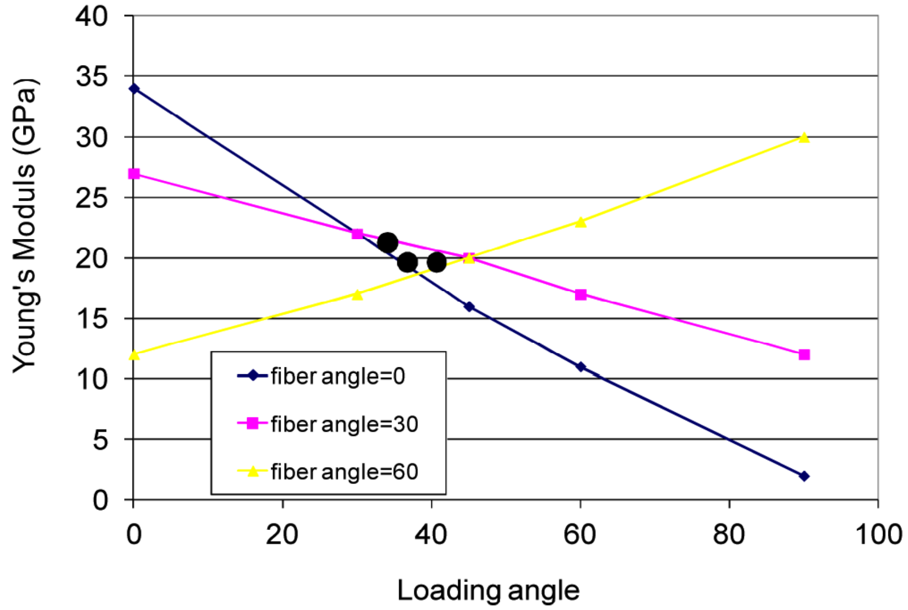


Figure 6 (Cont.)

(C) *f* = 30%

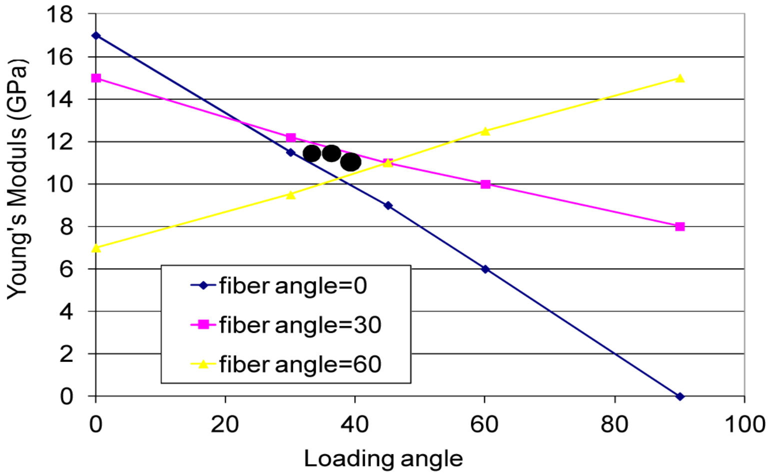
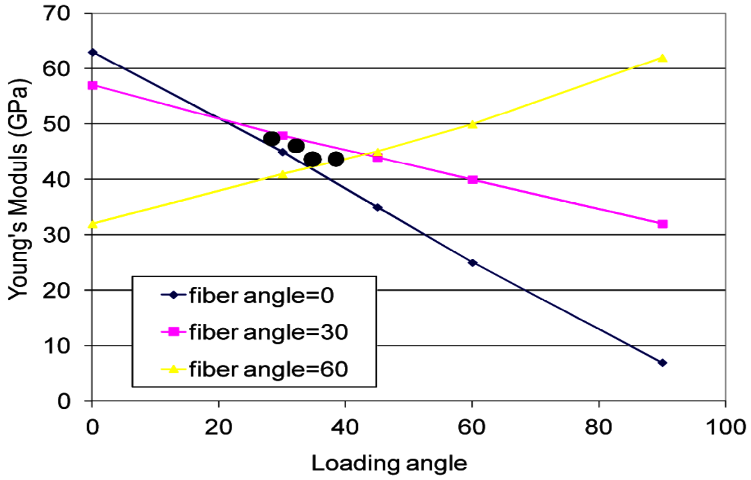


Figure 7: Optimum Design Points for S-Glass Type

(a) *f* = 90%



(b) *f* = 60%

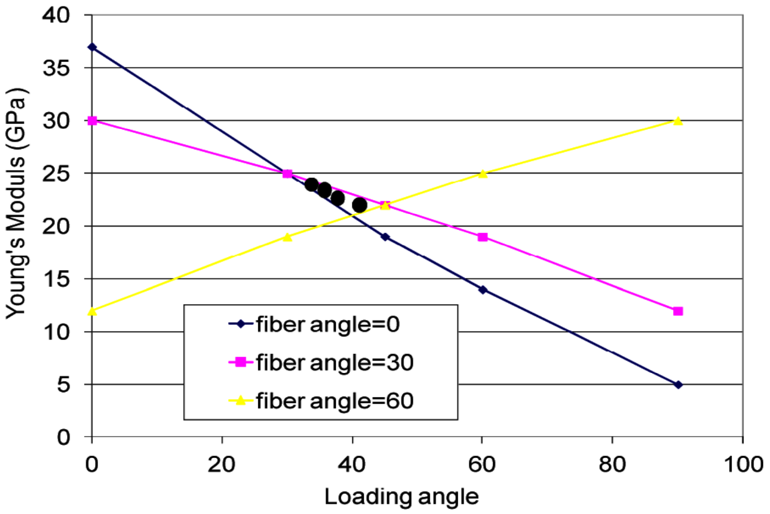
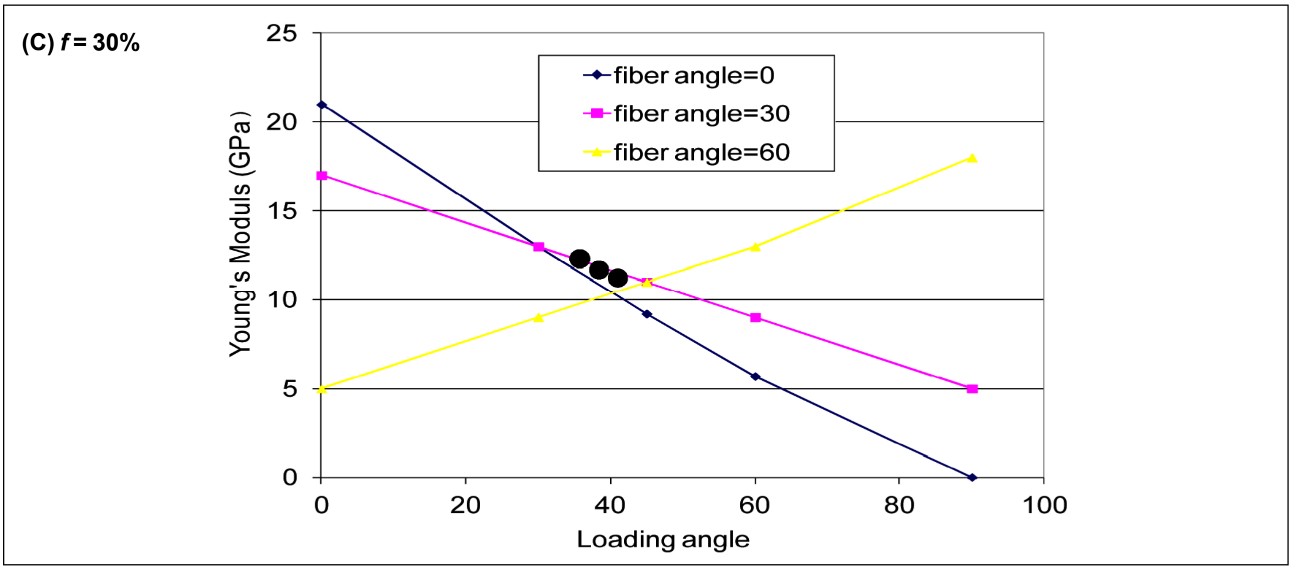


Figure 7 (Cont.)



CONCLUSION

The matrix polymer (epoxies) based materials are relatively weak, low-stiffness materials. Therefore, for structural applications, it is necessary to reinforce them with continuous or discontinuous fibers. The adding of glass fiber type E- and S-glass results in materials that have increased modulus.

The behavior of composite was presented in this work using a mathematical program. Nevertheless, this paper proposed a general model for fiber reinforced composites. The design points that needed to produce a high-stiffness, fiber-reinforced composite materials are determined. There are practical limits for composite designing that give the suitable young modulus. The stiffer fiber will give a wide range of practical case design. These design ranges have been found with the optimum points, or design values, lower and upper bounds. Most practical cases will be somewhere between these two values. Ranges of design points are affected by the type of fibers, where the highest ranges for practices designing show for the S-glass more than that for the E-glass. To obtain a high mechanical strength, the fibers have to be aligned parallel to the direction of the highest stress. The maximum value of the modulus of elasticity will appear when the fiber orientation angle equal to loading angle. It is recommended to make the verification and validation between the current model's findings and the experiments in case of multi layers and under cryogenics treatments.

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