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TENSILE DEFORMATION BEHAVIOR OF EPOXY COMPOSITES REINFORCED WITH THREE DIFFERENT WOVEN FABRICS.

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ABSTRACT

The tensile deformation behavior of epoxy matrix composites fabricated by the hand lay-up technique was investigated. Three different types of woven fabrics were used as reinforcements, namely: glass fibers (GF), carbon Fibers (CF), and hybrid reinforcement made of carbon and glass fibers. Four different volume fractions of GF were used, i.e., 9.2 vol. %, 18.4 vol.%, 27.6 vol. %, and 36.8 vol.%. Carbon and hybrid reinforcements were used at a volume fraction of 36.8% each. Besides, specimens of pure (unreinforced) epoxy were tested as a reference material.

It was found that increasing the GF volume fraction produced significant improvement in all mechanical properties of the epoxy matrix. The fracture stress of the composite with 36.8 vol.% GF is 375% that of pure epoxy. The composite with 36.8 vol.% CF showed a remarkable 780% increase in fracture stress compared to that of pure epoxy. The hybrid composite (HC) showed an improvement of 590% over the fracture stress of pure epoxy. Similar pattern was followed by other mechanical properties as will be discussed in detail.

The rule of mixtures (ROM) and the Halpin-Tsai (H-T) equations were used to analyse the obtained experimental results. It was found that the ROM gives an upper bound for the results with large differences between calculated and experimentally determined parameters. On the other hand, fracture stress values calculated according to H-T equations were so close to experimentally determined ones for all considered volume fractions. Values of elastic moduli calculated according to H-T equations diverted away from experimentally determined ones as the fiber volume fraction increased.

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Failure and fracture of the composites were investigated both macroscopically and microscopically. Fiber pull-out played a major role in the fracture of epoxy-GF composites. Interlaminar shear failure was found to be the dominant mechanism for fracture of CF composites. Hybrid composites showed a mixed mechanism. These fractographic results proved to be in good agreement with the mechanical testing results.

Key words: epoxy-woven carbon fibers - woven glass fibers - hybrid composite - mechanical properties - fracture.

Nomenclature :

E_f, E_m, E_l longitudinal modulus of elasticity of fibers, matrix, and composites, respectively.

E_{hl} longitudinal moduls of elasticity of hybrid interply composites.

E_g, E_c longitudinal modulus of elasticity of glass and carbon fibers, respectively.

V_m, V_f, V_c volume fractions of matrix, fibers, and carbon fibers, respectively .

σ_1 , σ_m, σ_f fracture stresses of the composite, the matrix, and the fibers, respectively .

σ_{hL} σ_g, σ_c fracture stresses of hybrid, glass, and carbon fibers, respectively

1. INTRODUCTION:

Despite the fact that fiber reinforced polymeric composites (FRPC) were first developed half a century ago, they are still regarded as relatively new materials. Applications of FRPC's include automotive car bodies, sports equipments, ships, air crafts, and so on[1,2]. FRPC's have many advantages which make them a potential substitute for conventional materials. Among these advantages are the light weight, exceptionally high specific strength and specific stiffness, and affordability[3].

Several techniques have been developed for FRPC's manufacturing, e.g. hand lay-up technique, prepreg lay-up, compression molding, resin transfer molding, pultrusion, filament winding, etc.[4,5,6].

Factors affecting the mechanical properties of FRPC's include: type of fibers, fiber volume fraction, geometrical arrangement and orientation of fibers, method of reinforcement (two-or three dimensional), type of matrix, etc[7,8,9].

The goal of the present work is to investigate the tensile deformation behavior of epoxy composites reinforced with three different woven fabrics. Reinforcements made of glass woven fabrics, carbon woven fabrics, and glass/carbon hybrid woven fabrics were used to produce these composites. Mechanical testing, macroscopic examinations, as well as scanning electron microscopy of the fractured specimens were conducted.

2. EXPERIMENTAL PROCEDURES

2.1. Materials:

Two different types of woven fabrics were used as reinforcements for the composites of the present work, i.e. carbon fibers and glass fibers. The two types were mixed in alternating layers to produce the hybrid composite (HC) reinforced by glass/carbon fabrics. Tables 1 shows the characteristics of each type of fibers as provided by the supplier.

Table 1a. Characteristics of Reinforcement Woven Fibers*.

Characteristic	Carbon fibers	Glass fibers
Color	Black	White
Specific gravity (gm/cc)	1.75	2.54
Modulus of elasticity (GPa)	235	72.50
Tensile strength (MPa)	3500	3450

* Supplied by Dexter Hysol Aerospace, Inc.

The resin used as a matrix for the present investigation is made up of two components. General purpose epoxy (MIL-A-8623), and polyamide resin as a hardener.

2.2. Fabrication of Specimens:

The hand lay-up technique was employed to manufacture the specimens of the present work. Wooden mold (300 * 75 mm) with well finished smooth surfaces was prepared, and its inner surfaces were covered by cellophane as a release agent. The fiber fabrics were cut to size and precalculated to give the required volume fractions when added to the matrix. Each ply was carefully laid-down in the mold cavity and resin was then uniformly applied all over its surfaces till saturation. Excess resin and air bubbles were squeezed out using a roller before placing the next ply. The same procedure was repeated for each of the layers. Thick metallic shims were placed at the corners of the mold to ensure constant laminate thickness. The mold was then covered using cellophane sheets, and a 15 kg platen was placed on top. The laminates were left to cure at a temperature of 70°C (158°F) for 2.5 hours as per supplier's instructions. Cured laminates were cut into standard rectangular specimens (204 * 12.7 mm) as per ASTM D3039-76 (1982). Finally, loading tabsfabricated separately-were bonded to the specimen ends. Fig. 1 shows a schematic sketch of the produced tension test specimens. Table 2.0 provides a list of conditions of tested specimens.

Table 2. List of Specimens' Conditions.

Reinforcement	Volume fraction %	Specimen thickness (mm)	No. of tested specimens
Pure epoxy	0 vol.%	3.275	3
Glass fiber*	9.2	3.275	3
Glass fiber	18.4	3.275	3
Glass fiber	27.6	3.275	3
Carbon fiber**	36.8	2.540	3
Hybrid: Carbon	36.8	2.54	3

* Glass fiber fabric is 0.30 mm thick. ** Carbon fiber fabric is 0.25 mm thick.

2.3. Fiber Volume Fraction Determination:

10 * 10 mm specimens of all fabricated epoxy reinforced composites were cut. Each specimen was immersed in a 30% concentration H2SO4 acid solution. Using a water bath and a magnetic-stir-type heater, each specimen was heated for about 7 hours under rapid stirring (500 rpm), to dissolve the matrix completely. After dissolution of the matrix, the fibers were extracted from the solution, carefully dried-up, and weighed. Using simple calculations, and knowing the density of fibers, its dry weight after extraction, and the volume of specimen before dissolution, it was possible to calculate the fiber volume fraction for each type of the composites.

2.4. Testing and Microscopic Procedures:

The tension tests were conducted in a universal testing machine equipped with computerized data acquisition system (DAS). The cross-head speed used for all tests was 2mm/min. Tests were carried out monotonically to fracture without interruption. Macroscopic fracture examination was conducted using 20X magnifying glasses, then zoom photography was used to record the results. Scanning electron microscopy was conducted on the fractured specimens to examine the fracture mechanisms under this type of loading.

3..RESULTS AND DISCUSSION

3.1. Tension Testing:

Fig. 2 shows the stress-strain curves of glass-fiber reinforced epoxy and that for unreinforced (pure) epoxy. The latter showed linear behavior to fracture which indicates brittle-like behavior. Such behavior is characteristic of epoxy thermosetting polymers[10]. The stress-strain curves for glass reinforced epoxy exhibited slight nonlinearity from beginning to fracture. This nonlinearity was also reported in the work of Yang, et al.[9], and S.H. Lee, et al.[11]. They attributed it to the structural changes in the woven glass fibers during deformation. However, the present authors believe that this nonlinearity is a manifestation of some sort of elastic-nonelastic

behavior which results from the strong interaction between the anelastic glass fibers and the brittle epoxy matrix.
This explanation is supported by the fact that all unreinforced epoxy specimens behaved in a brittle-fashion, while all glass fiber reinforced epoxy specimens showed non linearity. Jékabsons and Byström[12] reported that the nonlinearity of stress-strain curves decreases as the number of reinforcing plies increases. The experimental results of the present work is in good agreement with such finding.Incorporating woven glass-fibers (GF) in epoxy lead to significant improvement of all mechanical properties of the resulting composites compared to the unreinforced epoxy matrix. Table 3 a, b summarizes all mechanical parameters of the investigated composites of the present work. Adding 9.2 vol.% GF to the epoxy matrix did not lead to significant change in the strain to fracture compared to pure epoxy. However, as the volume fraction of GF increased to 18.4 vol.%, 27.6 vol.%, and 36.8 vol.%, the strain to fracture showed increases of 8%, 28% and 82%, respectively, Fig. 3.

Table 3.a. Mean Values of Tensile Properties for GFRE*.

Volume fractions of FGRE	Strain at fracture εf %	Fracture tensile stress Sf (MPa)	Longitudinal modulus of elasticity E (Gpa)	Modulus of resilience Ur (N.mm/mm3)
0	1.475	46.29	2.66	0.34
9.2%	1.45	42.56	5.67	0.454
18.4%	1.52	74.7	7.8	0.57
27.6%	1.88	108	9.6	1.02
36.8%	2.65	173.4	10.6	2.30

* Based on average of at least three specimens

This sharp increase in the strain to fracture of the composite as the glass fiber volume fraction increased to 36.8% shows a transfer from matrix controlled behavior to fiber controlled one. This result is in good agreement with the scanning electron microscopy work (SEM) which will be discussed shortly.

Table 3.b. Tensile Properties of the Different Composites*.

Type of reinforcement	Vf	Strain at fracture εf %	Fracture tensile stress Sf (MPa)	Longitudinal modulus of elasticity E (GPa)	Modulus of resilience Ur (N.mm/mm3)
GFRE	36.8%	2.62	173.4	10.6	2.30
Hybrid	36.8%	2.285	273.5	12.4	3.12
CFRE	36.8%	2.53	360.63	16.8	4.56

* Based on average of at least three specimens

he fracture stress of the GF composites showed a similar pattern of improvement compared to pure (unreinforced) epoxy. As the GF volume fraction increased from 18.4 vol.% to 27.6 vol.%, the fracture stress increased by about 133%. Similarly, as the GF volume fraction increased from 27.6 vol.% to 36.8 vol.%, an increase in fracture stress of about 275% is achieved, see Fig. 4.

The longitudinal modulus of elasticity, E of the glass-fiber reinforced epoxy showed significant improvement compared to unreinforced epoxy. At 9.2 vol.% GF the improvement in E is about 113% while at 36.8 vol.% GF the improvement is about 300%, Fig. 5. These results are expected for woven fabrics because transverse fibers act as stiffeners which raises the load carrying capacity of the longitudinal ones.

The modulus of resielience improved by 34% for the epoxy-9.2% GF, and the improvement reached 580% for the epoxy-36.8 vol.% GF. The modulus of resilience combines the effects of the woven fibers mentioned above, together with a toughening action given to the brittle epoxy by the woven glass-fibers, Fig. 6.

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It is clear from Fig. 2 that incorporating carbon fibers (CF) in the epoxy matrix lead to significant improvement in all mechanical properties of the resulting composites, see Figs. 3, 4, 5 and 6. The strain to fracture of the epoxy-36.8 vol.% CF is 2.53% which is little lower than that of epoxy-36.8 vol.%.

This result is in agreement with observations of macroscopic fracture-which will be discussed later-showing excellent bonding between carbon fibers and the epoxy matrix. The hybrid CF/GF composite showed the lowest magnitude of strain to fracture, i.e., 2.3%.

The fracture stress of the 36.8 vol.% CF composite showed an increase of 107% over that of the 36.8 vol.% GF one. Compared to pure epoxy, the CF composite achieved an improvement of about 680% in fracture stress. Table 3b also shows the elastic moduli of the different composites. As the GF volume fraction increased in the pure epoxy, the elastic modulus of the latter increased significantly. At 36.8 vol.% GF, the improvement in elastic modulus reached four times that of pure epoxy. CF composite at 36.8 vol.% gave an improvement of 632% compared to pure epoxy, while the improvement due to 36.8 vol.% hybrid composite is 470%. These results can be explained in view of the excellent bond between CF and the epoxy matrix compared to GF/epoxy bond, and also due to the high magnitude of the elastic modulus of carbon fibers (E = 235 GPa) compared to that of glass fibers (E = 72 GPa).

The modulus of resilience (UR) is an important parameter for polymeric fiber reinforced composites. It measures the ability of a material to absorb energy during elastic loading without yielding, then recover this energy completely upon unloading. Glass fiber composites showed the lowest modulus of resilience, while epoxy reinforced with carbon fibers showed the highest resilience.

3.2 Mathematical Analysis of Results :

The present authors conducted a study on the application of the rule of mixtures (ROM),and Halpin-Tsai (H-T) equations to the experimental results of the present study [13]. The ROM and H-T equations were selected since they are the simplest and most commonly used equations.

According to ROM, two moduli of elasticity can be derived, E1, and E2. Directions 1 and 2 represent loading directions aligned with, and perpendicular to fiber directions,respectively .

The first modulus, E1, is given by [2]:

$E_1 = E_f V_f + E_m (1-V_f)$ ……………………………………….(1)

The second modulus, E_2, according to the ROM, is given for transverse loading, i.e. and assumes isostress, i.e.:

$\sigma_c=\sigma_f=\sigma_m$ …………………………………………………………… (2)

Modulus E_2 is given by [2] :.

$$E_2 = \frac{E_f E_m}{V_m E_f + V_f E_m} \quad \text{………………(3)}$$

The ROM can also be used to evaluate the properties of composites reinforced by hybrid reinforcements that consist of two different fibers. In this case, another assumption is made in the derivation of the equations, i.e. that the longitudinal modulus of elasticity of the polymeric matrix is very small compared to that of the two types of fibers [4]. Thus, the elastic modulus, and the fracture strength of the composite are obtained from :

$E_{hl} = E_g (1 – V_m) + (E_c – E_g) V_c$………………………………… (4)

$\sigma_{hl} = \sigma_g (1 – V_m) + (\sigma_c – \sigma_g) V_c$……………………………….. (5)

Halpin and Tsai [5] developed empirical generalized equations that readily give quite satisfactory approximation of more complicated micromechanics results. These equations are quite accurate at low fiber volume fraction. They are also useful in determining the properties of composites that contain discontinuous fibers oriented in the loading direction [6].

The Halpin- Tsai (H-T) equations can be written as :

$M/Mm = (1 + \xi \eta V_f) / (1 - \eta V_f)$……………………………(6)

Where $\eta = \{M_f / M_m -1\} / \{M_f / M_m + \xi\}$……………….. (7)

Where M represents composite moduli, e.g. E_{11}, E_{22}, G_{12}, G_{23}, V_{12}, V_{23}, etc., M_f and M_m represent corresponding fiber and matrix moduli, respectively. V_f is the fiber volume fraction, and ξ is a measure of reinforcement of the composite material that depends on the fiber geometry, packing geometry and loading conditions. The term ξ is an empirical factor that is used to make equation [6] conform to the experimental data.

The function η in equation [7] is constructed in such a way that when Vf = 0, M = M_m, and when V_f = 1 , M = M_f. So, for $\xi \rightarrow o$:

$$\frac{1}{M}=\frac{V_m}{M_m}+\frac{V_f}{M_f} \quad \ldots\ldots(8)$$

And for $\xi \rightarrow \infty$: $M = M_f V_f + M_m V_m$………………… ..(9)

These two extremes bound the composite properties. Equation (8) gives a lower bound, while equation. (9) which is the well-known rule of mixtures equation gives an upper bound. Whitney [7] suggests ξ = 1 or 2 for the transverse modulus E_{22} depending on the fiber array type, e.g. hexagonal, square, etc.

3.2.1 Application of the ROM Equations to Present Study

Fig.7 a, b show plots of the experimentally determined modulus and fracture strength versus the same parameters calculated using the ROM equations.

It is clear that the ROM calculated parameters are higher in magnitude than the experimentally determined ones for all fiber volume fractions considered, and for all types of composite reinforcements

This shows that the ROM equations for calculation of properties of fiber reinforced epoxy and hybrid fiber reinforced epoxy give upper bound results.

3.2.2 Application of Halpin-Tsai Equations to Present Study

Equations [6] and [7] were used to calculate the elastic modulus and the fracture stress of the composites investigated in the present study . The parameters used were as follows :E_m = 2.66 GPa , σ_m = 57.2 MPa , E_g = 72.0 GPa E_{Car} = 320 GPa , σ_{car} = 3.53 GPa . Volume fractions varying from 9.2 vol. % to 36.8 vol.% were considered for glass fibers , while a single volume fraction of 36.8 vol. % was considered for each of the carbon , and hybrid reinforcements. The empirical parameter ξ was taken = 2.0 according to reference [6] . Figs. 8.a and 8.b show plots of the data obtained experimentally and those calculated according to Halpin–Tasi equations.

It is clear that at low fiber volume fractions , there is good agreement between the date obtained experimentally and those calculated according to H-T equations. As the reinforcement volume fraction increases , noticeable divergence is observed for the data of the elastic modulus. However , the data of the facture stress continues to show very good agreement up to the largest volume fractions of fibers investigated. Extrapolation of both the experimental and calculated fracture stress data show that H.T equations could be used satisfactorily to give accurate results .

It can be concluded that the H-T equations need to be modified in regards to calculations of the elastic modulus, but can be used to give satisfactorily good estimates of the fracture stresses for fiber reinforced epoxy.

4. ANALYSIS OF THE FRACTURE BEHAVIOR:

The tensile test specimens were tested up to fracture. The fracture behavior of the different composites was analyzed on macroscopic scale, and on microscopic scale using a scanning electron microscope (SEM). Besides, macroscopic analysis was conducted on pure epoxy specimens as a reference material.
Fig. 9-a shows the macroscopic fractograph of pure epoxy under tensile load. The fracture was completely brittle accompanied with fragmentation at the fracture section. The fracture appears to have occurred on two different planes. A plane normal to the loading direction, where fracture initiated and was accompanied with small fragments. And a plane makes an angle of about 20° with the load axis.
On the same figure, the macroscopic fracture surface of a 9.2 vol.% GF-epoxy composite is shown. It is clear that the fracture surface is normal to the loading direction which is characteristic of brittle fracture, although it is preceded by a small elastic strain of about 1.4%. Fiber pull-out is clear, and upon examination of the fracture surface, it was found to be preceded by localized matrix debonding and fragmentation. SEM examination of the fracture surface revealed matrix cracking away from the fibers (Fig. 9-b). this shows that the failure process started in the matrix by matrix cracking which lead to overloading of the fibers, which could be expected at this low volume fraction. Overloading of the fibers lead to fiber debonding and fiber pull-out. Such findings are in good agreement with similar findings reported by Todo, et al.[8].
Increasing the glass fiber volume fraction in epoxy did not cause significant change in macroscopic fracture mode or mechanism, Fig. 9-c. The fracture section is normal to the load direction and fiber pull-out is clear on the section. However, during testing,the fracture was not preceded by matrix fragmentation as noticed for the epoxy-9.2 vol.% GF. SEM fractography, revealed that as the glass fiber volume fraction increased above 9.2 vol.%, matrix cracking shifted from outside the fibers

to within the fiber bundles, see Fig. 9-d. This indicates that fracture started in the fibers which lead to matrix overloading. Rochardjo, et al.[17] studied unidirectional carbon-epoxy composites. They cited the fiber volume fraction, Vf, as the main parameter controlling the fracture mode. Their results shows a transition in fracture mode from a tensile fracture dominated by short fiber break at low Vf, to interlaminar shear failure dominated by long fiber pullout at high Vf. Such results are not in line with the results of the present work. A possible explanation for this disagreement is two-fold. First, the type of fiber used here is woven glass fiber while in the work of ref [17], it is unidirectional fibers. Secondly, the type of bond between the epoxy matrix and the glass fibers, which was found to be weaker than that established between carbon fibers and epoxy. This finding is in agreement with the work of Hayat and Suliman[18], who-reported poor adhesion and wetting characteristics between the phenolic matrix and glass fibers.

Fig. 9-c also shows macroscopic fractographs of the three composites, i.e. epoxy-GF, epoxy-CF and the hybrid composite epoxy HF, at the same vol. fraction of 36.8%, it is clear from the figure that fiber pull-out played a major role in the fracture process of glass reinforced epoxy, while shear failure with very little fiber pull-out dominated the epoxy-36.8 vol.% CF, while the hybrid composite showed a mixed mode type of fracture. These macroscopic results correlate well with the tension test results mentioned above. The increase in volume fraction of carbon fibers and the excellent bond between epoxy and the woven carbon fabric caused the two phase composite to act as a single-phase material. Thus, the matrix and fibers failed simultaneously as the load reached the fracture strength, i.e., the interlaminar shear strength is maximum compared to the other two composites. The fractograph, thus, indicates that the load carrying capacity of the material is effectively consumed in the case of carbon reinforcement while it is least consumed in the case of glass fibers reinforcement.

5. CONCLUSION:

Under tensile loads, unreinforced epoxy showed linear stress-strain behavior, woven-glass-fabric reinforced epoxy showed a slight non- linearity of the stress-strain behavior. Such non linearity decreased as the fiber volume fraction increased.

All mechanical properties of the investigated composites improved as woven fabrics were incorporated in the epoxy matrix. Such improvement increased as the fiber volume fraction increased.

Application of the ROM to the data of the present work indicated that the ROM gives upper bound values of the composite properties. However, application of H-T equations proved good agreement between calculated fracture stresses and experimentally determined ones for all fiber volume fractions. Calculated elastic moduli according to H-T are in good agreement with experimental ones at low fiber volume fractions but divert considerably at higher volume fractions.
The fracture surfaces for all specimens were normal to the load direction and all specimens fractured at mid section of the gauge length. At low glass fiber volume fraction, the fracture started in the matrix away from the fibers followed by fiber debonding, and fiber pullout. At high volume fraction, the fracture started in the matrix within the fiber bundles leading to fiber pullout and debonding. This was attributed to the weak bond between glass fibers and epoxy resin. At the same volume fraction, the carbon reinforced epoxy failed by interlaminar shear failure with minimum or no pullouts or debonding. This proved that the bond between carbon fibers and epoxy is excellent. Hybrid composites showed a mixed mode failure.

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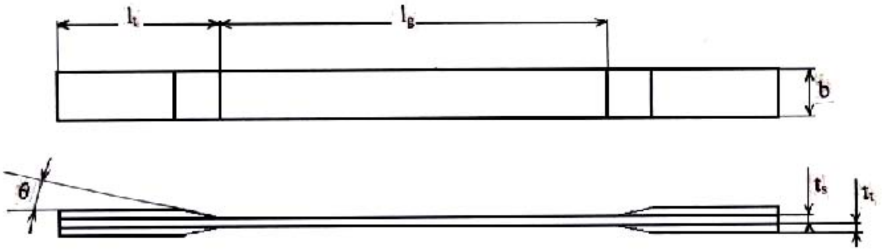

Geometry of the tensile test specimen according to ASTM D3039-76 (1989)

Dimensions of the tensile test specimen

Type of continuous fiber reinforcement	*Carbon/epoxy*	*Hybrid*	*Glass/epoxy*
Gauge length l_g (mm)	128	128	128
Tab length l_t (mm)	38	38	38
Specimen width b(mm)	12.7	12.7	12.7
Tapering angle θ (degree)	15^0	15^0	15^0
Tab thickness t_t (mm)	2	2	2
Specimen thickness t_s (mm)	2.54	2.75	3

Fig. 1. Schematic Sketch of the Tensile Test Specimen.

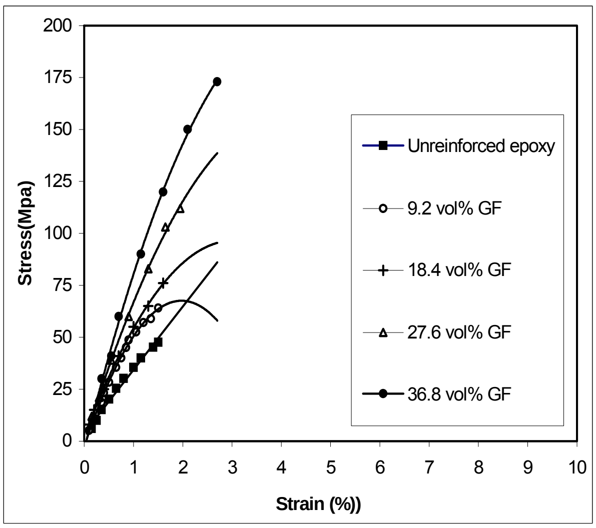

Fig. 2. Stress-Stain Curves of GF Reinforced Epoxy.

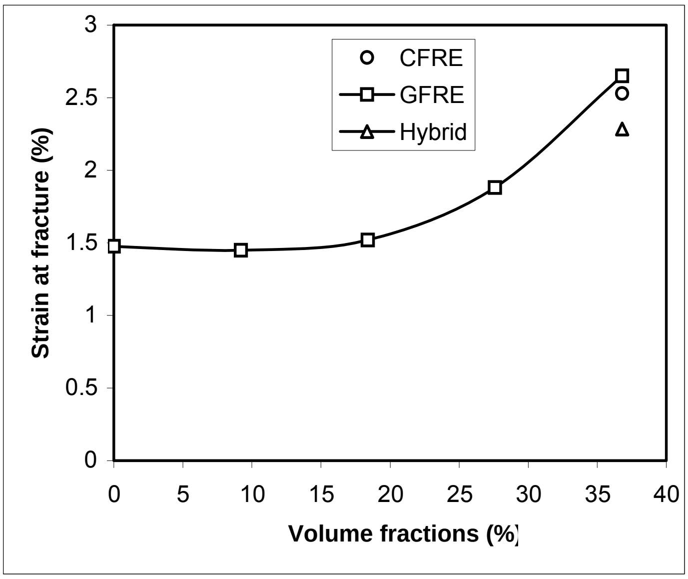

Fig. 3. Strain to Fracture Versus Volume Fraction of Different Reinforcments.

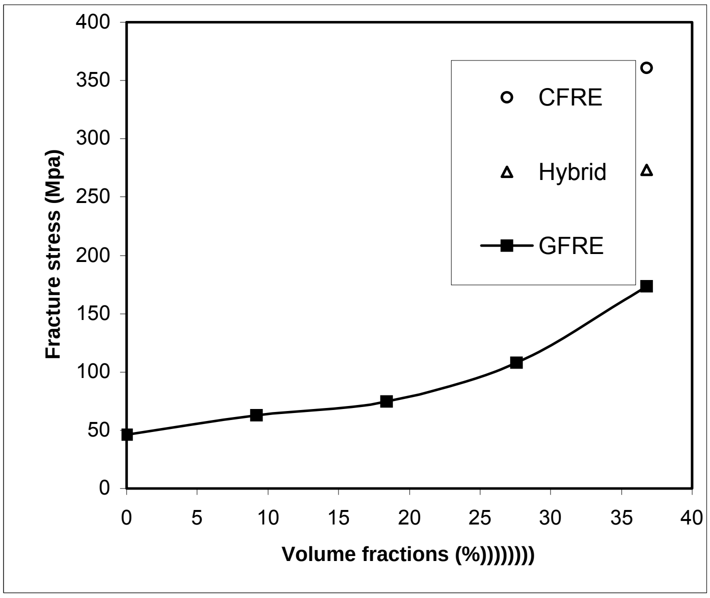

Fig. 4. Fracture Stress Versus Volume Fraction.

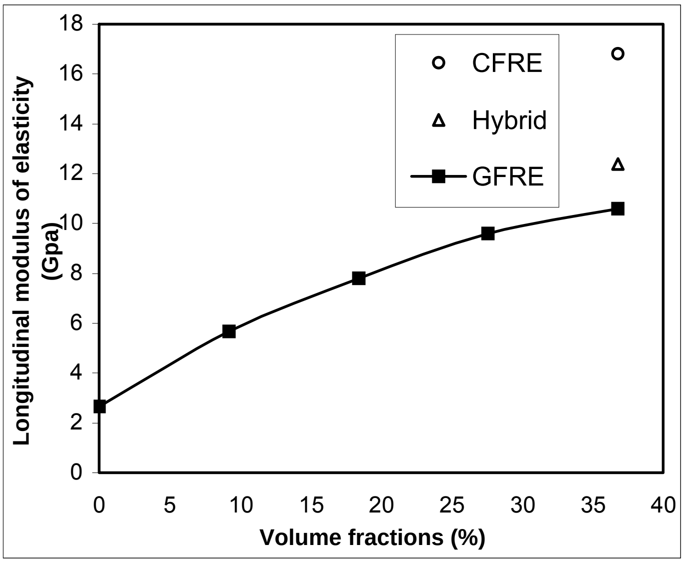

Fig. 5. Longitudinal Modulus of Elasticity Versus Volume Fraction.

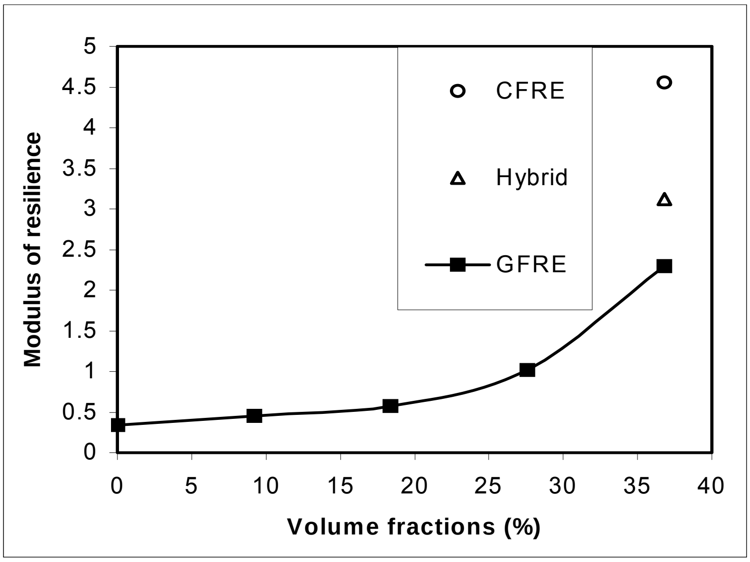

Fig. 6. Modulus of Resilience Versus Volume Fraction.

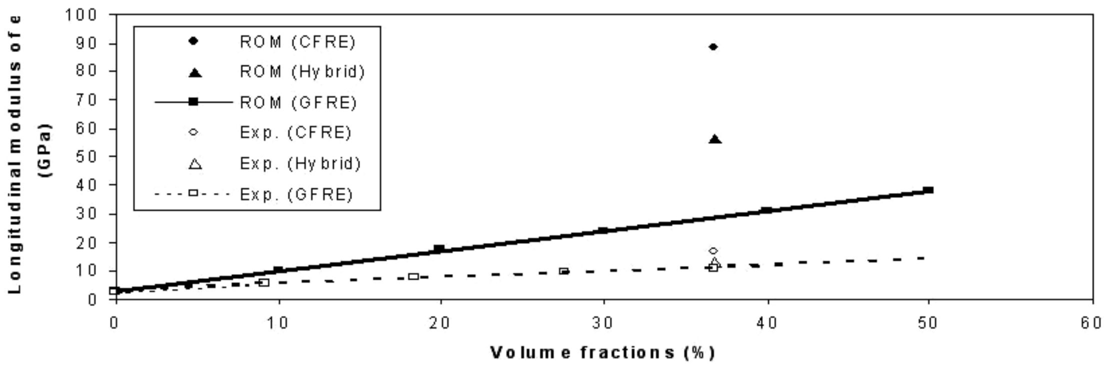

Fig. 7 a Application of ROM to Experimental Data For Elastic Modulus

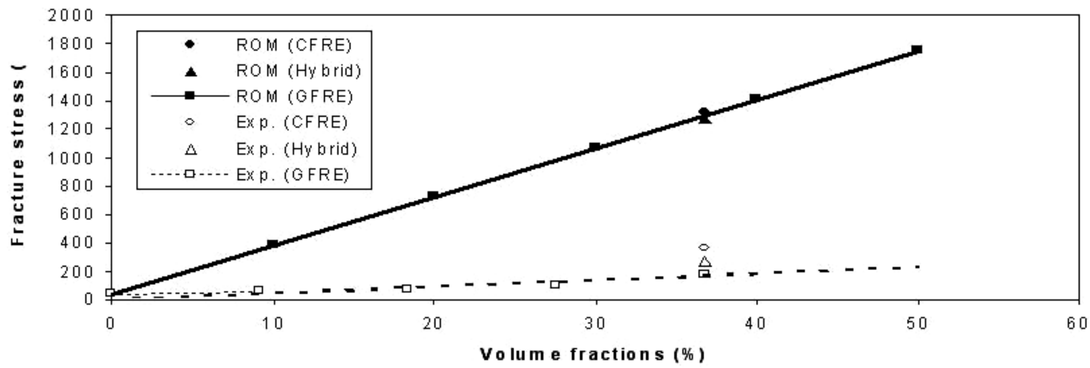

Fig.7.b Application of ROM to Experimental Data for Fracture Stress

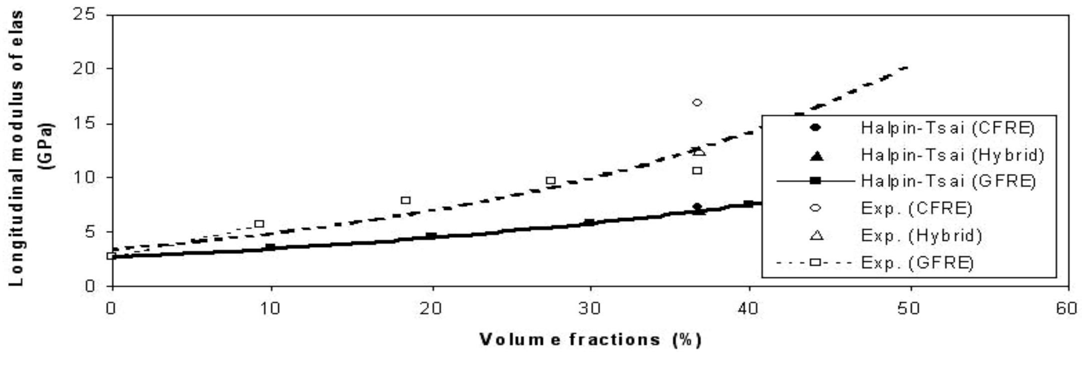

Fig. 8 a Application of Halpin-Tsai Equations to Experimental Data for the Elastic Modulus

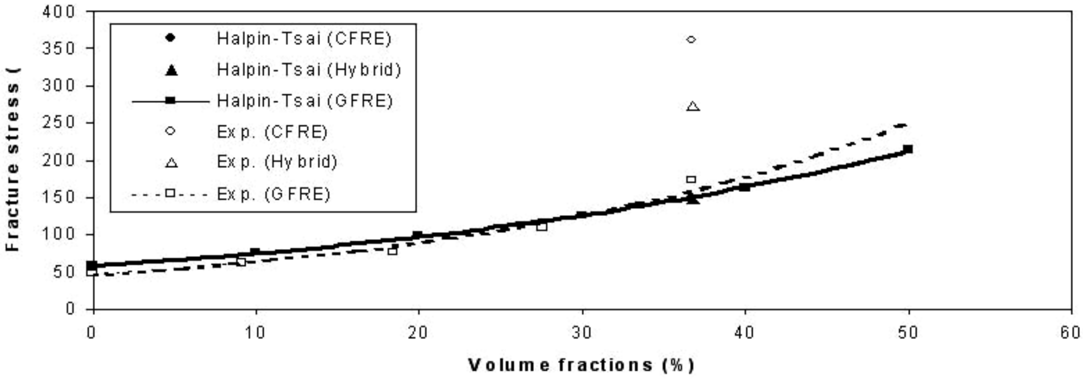

Fig. 8.b Application of Halpin-Tsai Equations to Experimental Data for the Fracture Stress

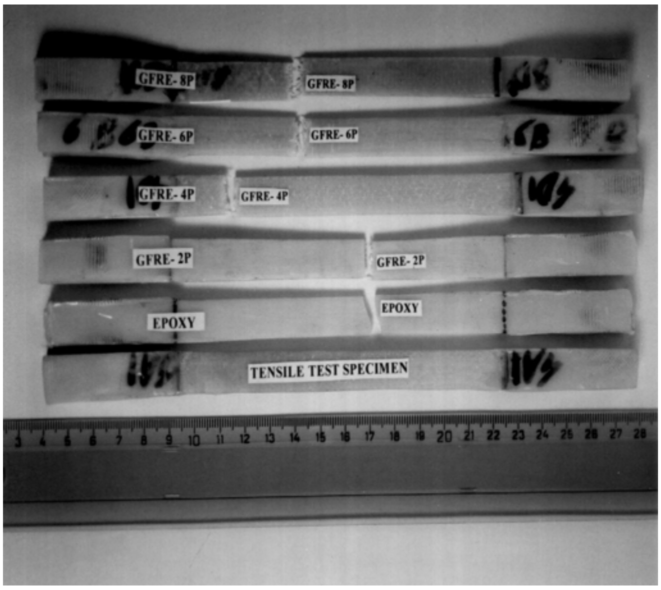

Fig. 9a: Macroscopic Fractograph of Pure Epoxy and Glass Fiber Composites.

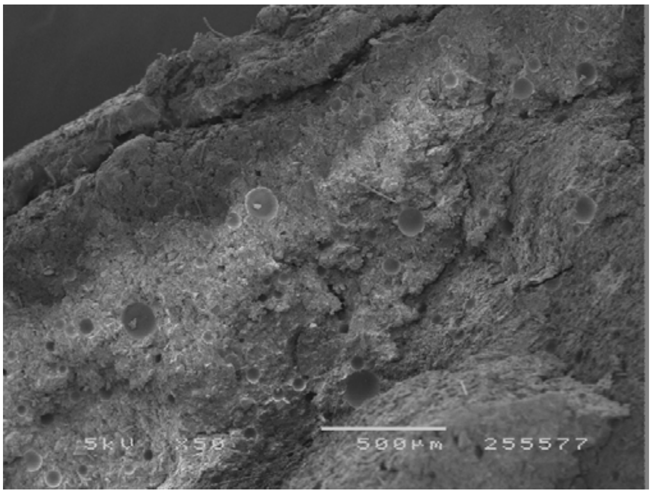

Fig. 9-b: SEM Fractographs for Epoxy-9.2 vol% GF

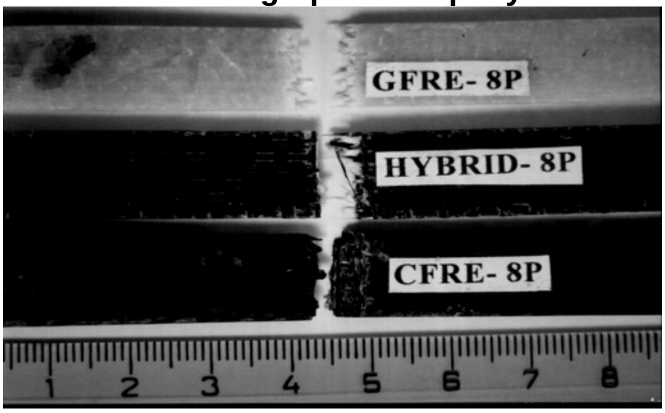

Fig. 9 c: Macroscopic Fractograph of the Different Composites.

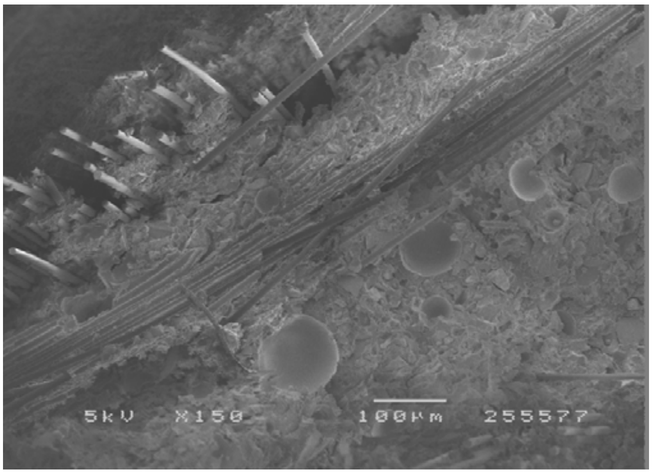

Fig. 9 d: SEM Fractographs for Epoxy-36.8vol% GF.