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Characteristics Composite Materials to be Used in Trans-Tibial Prosthetic Sockets

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Abstract

To initate a datebase on material properties on typical laminations used in belwo knee prosthetic socket (Trans-Tibial). The authors subjected samples of common prosthetic socket laminations to tensile, bending, and fatigue tests. Two varieties of lay up material (fibers) were each laminated separately with common resins (acrylic), resulting in four combinations of fiber/acrylic resin. Fibers made of carbon fiber and perlon fiber were used at different volume fractions. The result showed that socket prosthesis made of carbon fiber and perlon fiber (12 layers) has highest tensile and flexural strenght when compared to other laminations. Material test results indicate that the composite material (12 Layers) have better tensile and fatigue properties than composite material (8 layers). The ultimate tensile strength, and the modulus of elasticity composite material (12 layers) are higher than those of the composite material (8 layers) by 0.124% and 0.072% respectively, and by 0.1% and 0.185 for composite material (8 layers) with volume fraction of matrix equal 0.72). Vacuum technique is good process and this prevented cavites or defects in specimens.

Keywords: Composite Materials; Carbon Fiber; Testing of Materials; Trans-Tibial; Socket

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1. Introduction

Composite materials are widely applied in the manufacturing of prosthetic socket. The selection of material depends on several factors, such as patients effectiveness and the effect of material on human health. More prosthetic sockets are made of composite material. The main advantages of composite material are higher modulus, high strength to weight ratio or stiffness to weight ratio, and low density. The composite materials are consisted of reinforcement and matrix. The fiber is utlized as reinforcement materials such as Kevlar, carbon, glass, and natural fiber. There are two type polymers can be applied matrix such as thermoplastic and thermosets. The advantages of carbon fiber on another fiber is high strength, high modulus, and low density [1]. Acrylic resins are a type of thermosetting plastic. This resin is a light weight, good strength, and excellent wetting properties [2].

Several studies have been investigated to use the composite materials in prosthetic sockets. K. AL-Khazraji et.al, developed the vacuum molding technique to manufacture the lower limb prosthetic socket from five composite material (perlon, glass, carbon, hybrid (carbon and glass) and hybrid (carbon, glass and silica particle) with epoxy resin, the lamination subjects to tensile and fatigue test [3]. S. L. Philips et.al, used 24 varieties of lamination from fiber and matrix. The samples subjected to tensile and bending test, the authors classified the laminations into three groups according to the values of tensile test as shown in Table 1. The first group contains carbon fiber, second group includes fiber glass and last group is perlon, nylon, cotton and spectralon [4]. I. R. abd al-alrazaq et.al, developed a vacuum technique to fabricate the socket from 8 layers of perlon with acrylic. The sample is subjected to tensile, creep, and fatigue test. The result shows the perlon (8 layers) has low mechanical and fatigue properties. Ultmiate stress of current study that used 12 layers increasing at rate 78.68% than ultimate stress of 8 layers (perlon only) that can used this study [5]. D. A. Taylor et.al, tested composites materials such as carbon fiber, fiberglass, and nylon with three type of matrix, acrylic, polyester and epoxy. These materials were subjected to tensile test. The authors studied the effects of length fiber, orientation, volume fraction, and processing technique on mechanical properties [6].
V. Faulkner et.al, established a manufacturing technique and criteria for knitting the fiber into stockinet material. The determination the strongest and lightest weight of fiber or combination fiber and finding best matrix for lamination these fiber in prostheses [7].
A. P. Irawan et al, applied the tensile and bending test on specimens made from natural fiber [8].

In above studies, it was found that not much work has been reported in improving the phyasical, mechanical, and fatigue properties which is dependent on volume fraction. The aim of this studyis to characterize the composite materials made of from carbon and perlon with acrylic resin.

Table 1. Range of carbon fiber used in prosthetic lamination [4].

Strength Range	Fiber Types	Ultimate strength (MPa)	Young's modulus (GPa)
High	Carbon	236-249	20.6-25.5

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2. Characteristics of the reinforcement and matrix mixture

The mechanical properties and physical properties may be obtained by application of simple rule mixture. These properties depend on volume fraction or weight friction. Fiber volume fraction and matrix volume fraction are defined of Ref. [9]. The following equations explained the volume fraction of fibers and matrix.

$$Vf = \frac{vf}{Vt} \quad (1)$$

$$Vm = \frac{vm}{Vt} \quad (2)$$

The following formula is applied to calculate the theoretical density according to the role of mixture.

$$\rho th = \rho f\, Vf + \rho m\, Vm \quad (3)$$

$$\rho ex = \frac{W}{V} \quad (4)$$

$$Porosity\,\% = \frac{\rho th - \rho ex}{\rho th} \quad (5)$$

3. Experimental Procedure

For manufacturing the specimens by vacuum technique, the mold of gypsum is prepared with dimensionality (30 lenght, 15 width and 5 thickness) cm as shown in figure 1

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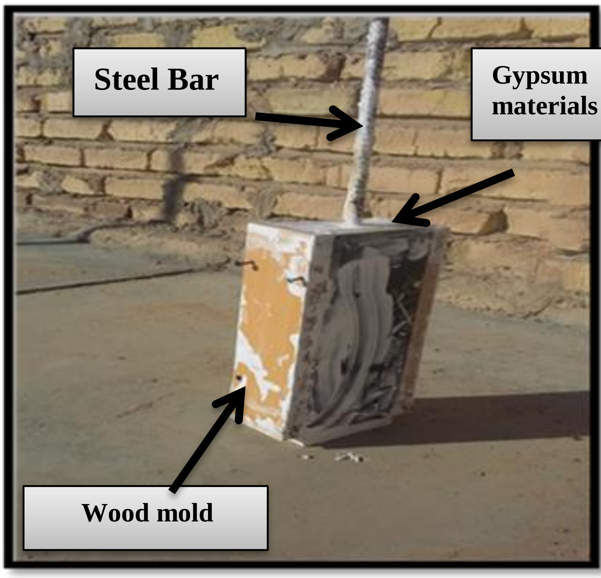

Figure 1. Positive mold

Composites materials needed to manfacturing of specimens for this study are: carbon fiber and perlon fiber with acrylic resin. Other materials needed for preparation of specimens were: Hardening powder, PVA polyvinyl alcohol as shown in figure 2.

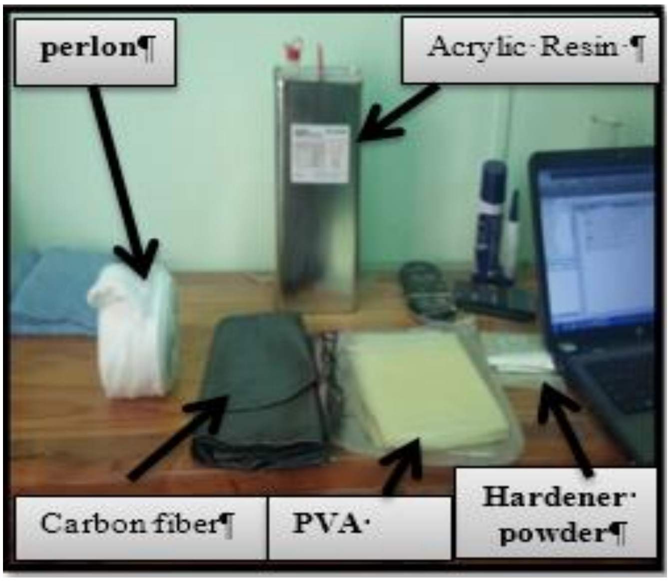

Figure 2. Materials used in this study

The method of preparation of composite specimen is called vacuum method which prevents cavities or defects and it is as follows: Preparing the gypsum block which contains steel beam.

The inner face of mold was covered with layer of nylon made from (PVA) polyvinyl alcohes, so as that to prevent the adhesion of acrylic resin with mold. Carbon and perlon fibers of the stochinette were then pulled over mold as explined in table 2. The outer PVA pulled over fibers. Acrylic resin was mixed with hardner according to fiber volume fraction (Vf) and matrix volume fraction (Vm) as shown in table 3. Hardener used in this study is 2% of resin for all groups.

Table 2. Number of layers and arrangement of layers

Name of group	Number of Layers	Lamination lay-up procedures
A	8	2perlon-1carbon 2perlon-1carbon, 2perlon with acrylic resin
B	8	3 perlon- 2carbon-3perlon with acrylic resin
C	12	2 perlon-1carbon-2perlon-2carbon-2perlon-1carbon-2perlon with acrylic resin
D	---------	Pure acrylic

4. Testing of material

Samples test were prepared by CNC cutting machine of the laminations. All test specimens were conditioned according to the room temperatures with relative humidity 50%.

4.1 Tensile Test

Tensile testing is referred to ASTM D-638 standard [10]. The speed rate was 2 mm/min. The dimensions of the specimens for tensile test were 50 * 13 mm (original length * width) while thickness for all group explained in table 3. Three samples for each lamination were tested. The process of tensile test and position of the sample as shown in figure 3 and 4. Each sample was subjected to load until failure. Based on tensile testing will be obtained for tensile strength and Young's Modulus of socket trans-tibial prosthetic materials.

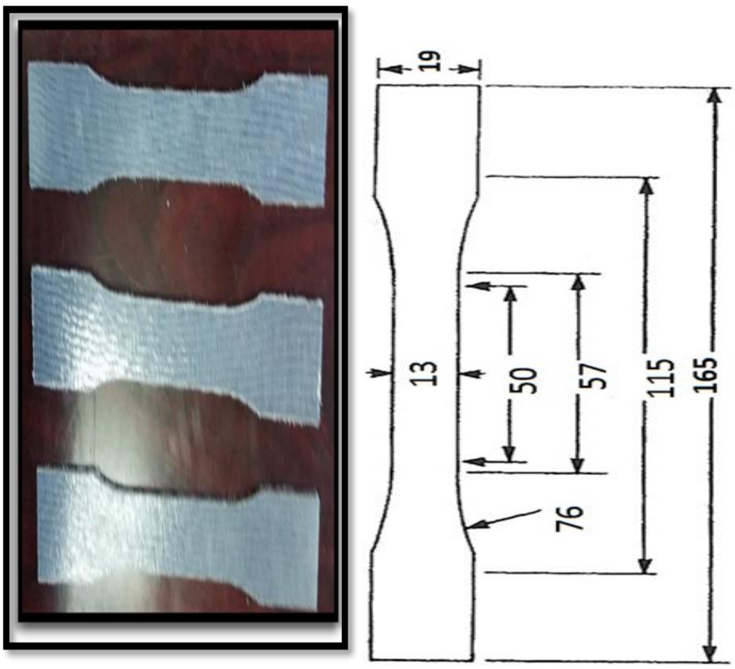

Figure 3. Standard specimens of tensile test [10]

Figure 4. Tensile test machine

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4.2 Bending Test

Flexural testing is referred to ASTM D-790 standard by using the Universal Testing Machine[11]. The load was applied midway between two supports with speed rate 5 mm/min as shown in figure 5. The dimensions of the specimens for bending testing were 100 x 20 mm (length x width) while the thickness is reported in table 3. Three samples for each lamination tested for flexural testing. Each sample was subjected to load until failure. Under the load, the bottom of specimen subjected to tension, the top of specimen subjected to compression. Bending stress equals to zero at neutral axis.

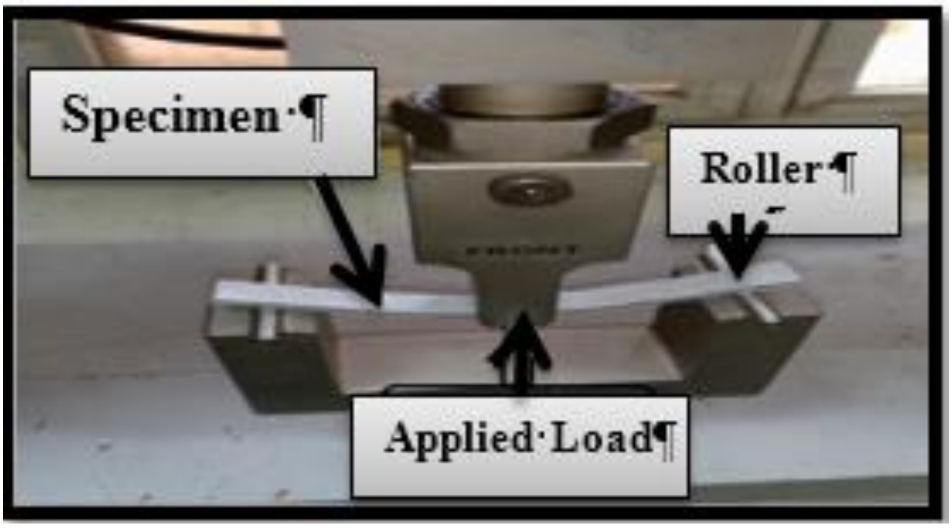

Figure 5. Flexural test machine

4.3 Fatigue Test

Fatigue test is referred to Annual [12] by using alternating bending fatigue (HSM 20, 1400 rpm, voltage 230 V, frequency 20 Hz, and power 0.4 Kw) as shown in figure (6). Fatigue test of material specimens was carried out at Baghdad University.

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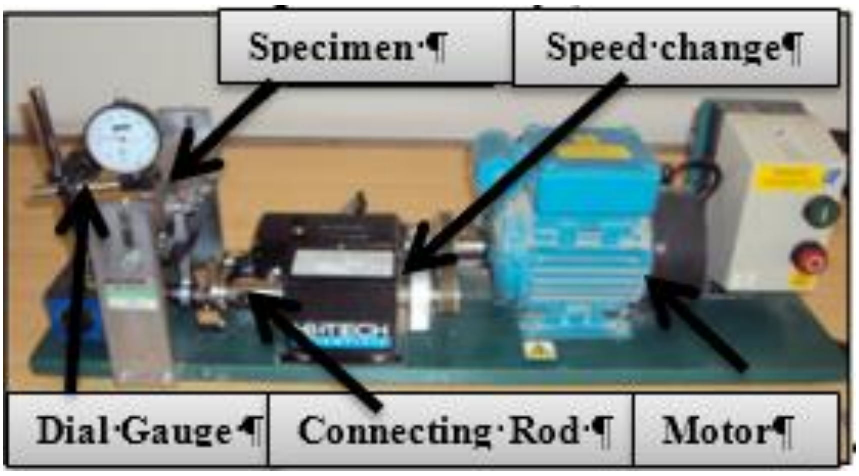

Figure 6. Fatigue test machine

The samples were subjected to deflection perpendicular to the axis of samples at one edge of samples, and the other edge fixed. The dimensions of the specimens for fatigue test were 100 * 10 mm (length * width) [12]. The speed of test depends on the type of material and deflection, the composite material is subjected to lower speed compared to high speed with metal. Eight samples were tested for fatigue test. A dial gage is used to select the deflection. The stress is applied on specimen until crack appears the or fracture is occurred. The S-N curve can be found by two methods:

- Conventional method: the bending stress can be estimated from following equation.

$$\sigma a = \frac{(1.5\, Eflexural\delta t)}{l^2} \qquad (6)$$

- Monogram method: this method carried out on chart by application the following formula.

$$\sigma a = \frac{Eflexural\delta t}{150\, Q} \qquad (7)$$

$$Q = correction\, foctor$$

In this work, conventional and monogram method are used [12].

5. Results and discussion

5.1 Physical properties

Table 3 shrefers to the physical properties of each lamination. The theoretical and experimental densities of the composites along with porosity are reported in Table 4 .

Table 3. Physical properties

Name of lamination	Vm (%)	t mm	Vf (%)	W g
A	0.590	1.8	0.409	6.2
B	0.76	3.66	0.24	10.6
C	0.612	3	0.388	10.3
D	1	4	0	5.8

Table 4. Experimental and theoretical density

Name of lamination	A	B	C	D
Theoretical density(g/cm^3)	1.209	1.212	1.228	1.22
Experimental density (g/cm^3)	1.185	1.19	1.2	1.22
Porosity %	1.9	1.8	2.2	0

It is observed that the composite density values are calculated theoretically from volume fraction by Equation 3 are not equal to the experimentally actual measured value as shown in Figure 7.

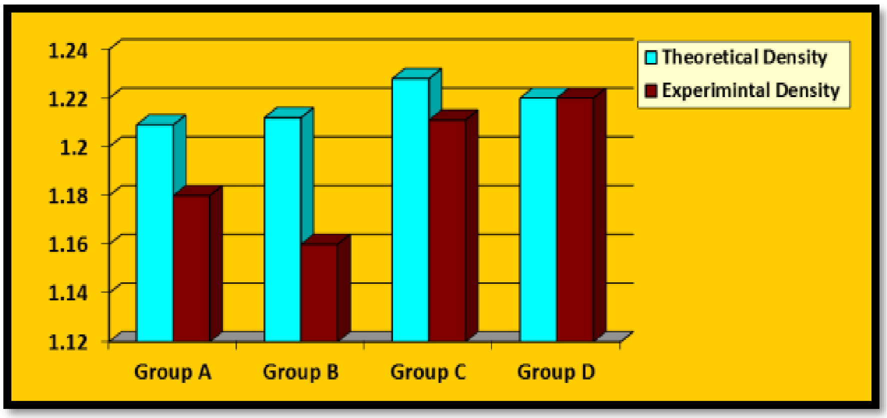

Figure 7. Difference between theoretical and experimental density.

This difference is due to presence of porosity in laminations. The porsity shows that more porosity are found in lamination with increasing of volume fraction of fiber [13]. The porosity of the composites are presented in Table 4. It is observed that porosity exist in the composites since the experimental true densities are lower than the theoretical densities. The porosity of composite material is incresed with increasing density. It is however encouraging that percent porosities are between 1.8 and 2.2% which is with in the acceptable range of 5% porosity reported in literature review as the maximum permissible in cast metal matrix composites [14].

5.2 Tensile Test

Table 5 represent the result obtained from tensile test. Group C composite presented a tensile strength of 152.5 MPa, Group A of 135.6 MPa, Group B of 76 MPa and Group D of 28 MPa. It can be seen that the ultimate strength which is resulted from Group C is highest than that of Group A (12.46%) and Group B (100.65%).

Table 5. Result of tensile test

Name of lamination	Ultimate strength (MPa)	Young of modulus (GPa)
A	135.6	3.414
B	76	3.08
C	152.5	3.65
D	28	0.975

Several parameters can greatly effect the strength and performance. The fiber length, orientation and volume fraction, and processing techniques used to manufacture the composite effect composite performance, The increases of fiber length and volume fraction can improve the ultimate stress [15]. Carbon fiber used in this study is a continuous fiber. Group C produces an young's modulus of (3.65 GPa) highest compared to Group A (3.414 GPa) and (3.08 GPa). High Young's Modulus will result in a total contact socket and produces a best comfort level for patients. This condition should be considered in choosing socket materials. Classical prosthetic socket are usually made from rigid materials although some prefer a flexible socket (high Young's Modulus) supported by rigid frame as it provides better comfort during gait cycle and sitting [16]. Figure 8 shows typical stress-strain curves obtained for three groups using carbon fiber and perlon fiber, respectively the ultimate tensile stress is the highest point. The ultimate stress and young modulus increased with increasing of layers of fiber. These result, is in good agreement with reported properties of these two materials [7]. The specific strength and specific modulus are presented in Table 6. A materials with high specific strength will be suitable for manufacturing the Trans-Tibial socket. This means that the materials has a light weight with high strength. These parameters are important in such safety conscious applications [17].

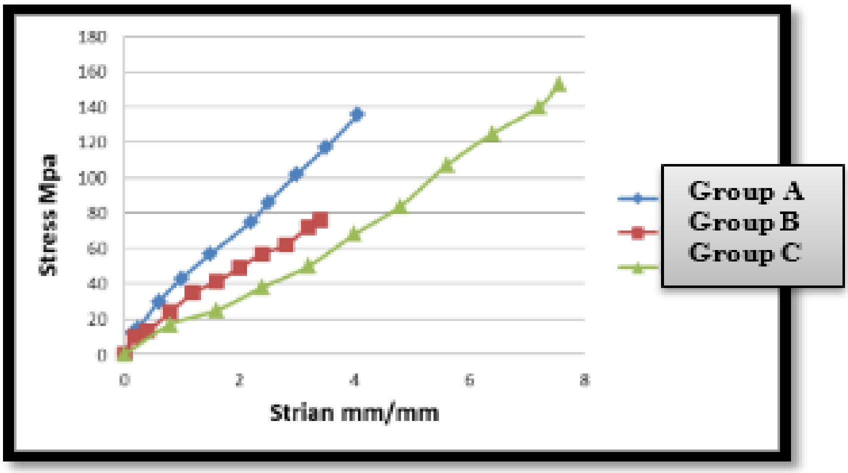

Figure 8. Stress-strain curve

Table 6. Result of specific strength and specific modulus

No.of lamination	Specific strength	Specific modulus
Group A	114.4	2.881
Group B	63.86	2.58823
Group C	127	3.05

5.3 Bending Test

The flexural strength of socket materials is introduced in Table 7 for Group A and Group C. The flexural strength of Group C is 242.2 GPa. This result is the highest compared to Group A composite materials (124.03 GPa). Flexural strength from socket prosthesis is needed to support the body weight and extreme movement, which way occurred from the process of locomotion and other dynamic activities of the users [18].

Table 7. Result of bending test

Name of lamination	Flexural strength (MPa)	Modulus of elasticity (GPa)
Group A	124.03	4.906
Group C	242.95	9.021

5.4 Fatique Test

The S-N curve is used to explain the fatigue failure of material, the stress over number of cycle of specimens are shown in Figure 9. The highest stress that a specimens can resist for an infinite of cycle without fracture is called fatigue limit. The S-N curve fatigue limit is 63 MPa and Number of cycle is 1.14 * 10^6 cycle. These results are acceptable as compared with specimens used only four layers carbon [19]

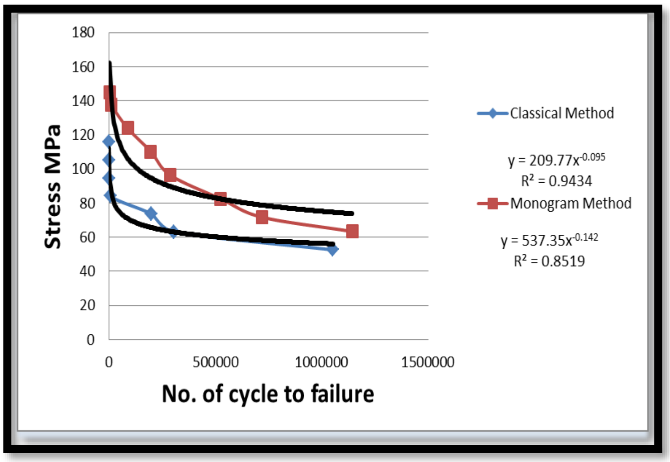

Figure 9. S-N curve

In general, the fatigue limit (strength) of materials is proportional to its tensile strength, hence materials with higher maximum tensile strength possess higher fatigue limit. The curve fitting equations which express the fatigue behavior of the samples and its relative correlation factor (R2) are given in Table 8. It is noted that these equations have relatively high correlation factor which indicate that the experimental data are well explained by log formula, since the correlation factor is a handy measure of the goodness of fit

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Table 8. Curve fitting equation, fatigue limit and correlation factor

Name of methods	Fatigue limit MPa	Curve fitting equation	Correlation factor R^2
Classical	52.61	$Y=209.77X^{-0.095}$	0.9434
Monogram	63.4	$Y=537.35X^{-0.142}$	0.8519

6. Conclusions

The experimental study the characterize of composite materials used in socket prosthetics leads to following conclusions:

1. The porosity of composite is increased with increasing density. Group B gave minmum porosity.
2. The values of experimental density of all groups are lower than that theoretical density, four layers of carbon with eight layers of perlon have the highest density when compared with other groups.
3. Ultimate stress of group C increasing at rate 12.6% and 100.65% than ultimate stress of group A and B respectivly that can used for fabrication trans-tibial socket.
4. Group C has higher mechanical properties and fatigue charactersics than other groups. Group B gave the lowest values in all measured properties.
5. The range of amplitude deformation by monogram method less than that of deformation by conventional method, thus the number of cycle by monogram method is more regular than conventional method.
6. The reasons for failure of specimens under test can be observed with the naked eye and can be referred tothree reasons. The first is due to the poor quality of the materials used. The second is due to the separation of the layers as a result of poor casting process (casting process conditions). The last is due to error test apparatus .

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Notation

Symbol	Definition	Unit
ASTM	American society for testing and material	
Eflexural	modulus of bending	GPa
l	*Length of sample*	*mm*
t	thickness	mm
V	*Volume of sample*	cm^3
Q	*Correction Factor*	
Vf	*volume fiber fraction*	
Vm	*Matrix volume fraction*	
vf	*Volume of fiber*	cm^3
vm	*Volume of matrix*	cm^3
Vt	*Volume total*	cm^3
W	*Weight of sample*	*g*
ρ_{th}	*theoretical density*	g/cm^3
ρ_f	*density of fiber*	g/cm^3
ρm	*density of matrix*	g/cm^3
ρ_{ex}	*experimental density*	g/cm^3
σ_a	*amplitude stress*	*MPa*
δ	*Amplitude Deflection*	*mm*