Iraqi Journal of Physics, 2010 *Vol. 8, No.11, PP. 110 - 117*

Fatigue Behavior Of Chopped Carbon Fiber Reinforced Epoxy Composites

Mohammed Hussein B. Hassan and Ekram .A.AL-Ajaj

University of Baghdad, College of Science, Department of Physics

Abstract

Hand-lay up method was used to prepare the samples made of epoxy (EP) as a matrix reinforced with chopped carbon fibers (CCF). The fatigue behavior of epoxy resin /chopped carbon fiber composites was studied with different weight percentage of chopped carbon fibers (2.5%,5%,7.5%,10%,12.5%). The fatigue test was carried out under alternate bending method, which was made by applying sinusoidal wave with constant displacement (15mm), stress ratio R=-1,and loading frequency 10Hz, which is believed to give a negligible temperature rise during the test. The results of the maximum stress, fatigue strength, fatigue limit and fatigue life of the tested composites are calculated from stress(S)-number of cycles(N) (S-N) curves.

It was shown that increasing weight percentage of chopped carbon fibers increase the values of maximum stress for all composites, while the values of fatigue strength, fatigue limit and fatigue life increasing for all composites except the composite with reinforcing weight 12.5%, which was subjected to rapid failure (fracture). This failure could be due to the debonding of the chopped carbon fibers from the matrix epoxy.

Keywords
fatigue behavior
epoxy resin (EP)

Article info
Received:
Accepted:
Published:

سلوك الكلل لمتراكب الايبوكسي المدعم بألياف الكاربون المقطعة

محمد حسين بشار حسن وأكرام عطا العجاج

جامعة بغداد - كلية العلوم - قسم الفيزياء

الخلاصة

حضرت العينات للفحص بطريقة التشكيل اليدوي من مادة الايبوكسي كمادة أساس ودعمت بألياف الكاربون المقطعة chopped carbon fiber(CCF).

تمت دراسة سلوك الكلل لمادة الايبوكسي ومتراكباتها المدعمة بألياف الكاربون المقطعة وبنسب وزنية مختلفة هي 2.5%, 5%, 7.5%, 10%و12.5% بطريقة الثني المتناوب.

أجري فحص الكلل بطريقة الثني المتناوب وبتسليط حمل جيبي بإزاحة بقيمة ثابتة مقدارها 15mm وبنسبة أجهاد R=-1 وبتردد 10Hz والتي يعتقد بأنها تمنع أي زيادة في درجة الحرارة. وتم حساب أعظم جهد, مقاومة الكلل, حد الكلل وعمر الكلل لكل المتراكبات من منحنيات الإجهاد(S) مع عدد الدورات (N) وأظهرت نتائج الفحص تأثير زيادة نسبة التدعيم على سلوك الكلل للعينات وذالك بزيادة قيمة أعظم جهد لجميع المتراكبات وكذلك بزيادة قيم مقاومة الكلل,حد الكلل وعمر الكلل لجميع العينات باستثناء العينة ذات النسبة الوزنية 12.5% والتي تتعرض للفشل السريع(الكسر) ويحدث الكسر بسبب عدم الترابط القوي بين ألياف الكاربون ومادة الأساس الايبوكسي.

Introduction

It is generally acknowledged that carbon fiber reinforced polymer (CFRP) composites should, in principle, be fatigue resistance provided that fibers carry the major part of the load and are not so extensible as to permit large elastic deformations of the matrix [1]. CFRP composites are widely used in producing components by injection or compression moulding such as in aerospace, automotive, military application as safety helmets, household furniture and other application [2,3].

Fatigue concerns the damage of materials when subjected to cyclic loading at the stress level that is less than their ultimate static strength. Fatigue damage is known to be a slow process of which the development depends on the microstructure of the materials. For homogeneous materials, the fatigue behavior is often characterized by an early crack that dominates the damage development and leads to the final fracture. For inhomogeneous materials, such as fiber or particulate reinforced polymers, the fatigue damage at an early stage is often diffuse in nature, as the crack can be initiated from multiple sites. In this case, the dominant crack may not be apparent until it is very close to the final fracture [4,3]. Carbon fiber composites had an excellent fatigue behavior (test results were generally presented in the form of stress_ number of cycle [S_N] curves) with nearly flat S_N curves [5,6,1]. The effectiveness of fiber reinforcement depends on many variables including the resins used, the quantity of fibers in the resin matrix, length of fibers, form of fibers, direction of fibers, adhesion of fibers to the polymer matrix, and the impregnation of fibers with the resin. Composites that have randomly-oriented fibers are isotropic in their mechanical and physical properties, in other words, the strength of the fiber-reinforced composite (FRC) is not related to the direction of the stress.[7,8,3].

Experimental details

Raw Materials and Preparation Method

The materials used to prepare the composites are epoxy resin (Leyco-Pox 103) with the hardener formulated amine supplied by Leyco Chem. Leyde industry as a matrix, (density 1.08 gm/cm^3), and chopped carbon fiber with length 8 mm (density 1.78 gm/cm^3 and diameter 4.2 μm).

The composites were prepared from epoxy resin as a matrix and carbon fibers as reinforcement with fiber weight percentage wt% as 2.5%,5%,7.5%,10%,12.5%, by using hand lay-up method. The mould stage of glass plates for casting the composite sheets, were prepared from cleaned waxed glass plates. The wax was applied to prevent the adhesion of composite sheets with glass plates. To prepare the composites sample, the epoxy matrix poured on the dried waxed glass plates using a paint brush to obtain a thin layer of resin, the carbon fibers mixed with another amount of epoxy matrix by using a rubber roller to enhance impregnated for matrix to fibers and placed on the resin layer and add some of resin again to the upper surface of the carbon epoxy mixture sheets were pressed to drive away the voids of air from the composites. The composites sheets were stored at room temperature for 3 days and then post-cured for 30 minute at 50 ^{o}C.

Fatigue Testing Procedure

The fatigue testing was conducted by using the fatigue machine (type PWOG made by CARL SCHENCK AG.). It is suitable for alternative bending test on flat specimen bending fatigue namely displacement controlled or strain controlled, imply pure tension and compression to test the prepared sample.

The fatigue procedure were performed at room temperature under constant displacement (U=15 mm) to obtain their number of cycles to failure (N). Testing was performed with fully reversed bending fatigue test, then bending stress (σ) verses number of cycles curves (σ-N) were plotted for the prepared composites. The type of loading was sinusoidal wave with stress ratio R= -1.

$$R = \frac{U_{min}}{U_{max}} = -1 \qquad \ldots\ldots\ldots\ldots(1)$$

Where: U_{min} is the minimum displacement amplitude.

U_{max} is the maximum displacement amplitude.
The bending stress (σ) of the spring is determined from the following equation:

$$\sigma = \frac{m_b}{W} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Where: $W = \frac{h^2 b}{6}$

m_b=the bending moment (Nm)(was calculated from the standard curves between indication on dial gauge and the bending moment).
b = the width of specimen waist (20mm).
h = thickness of specimen (3mm).

The fatigue loading frequency was set at 10Hz since at this frequency there is no evidence of thermal softening of any testing sample, also, the fact there is no significant heating to 10 Hz, as temperature rise dose not exceed 5 ^{o}C [9,10,4].

Fatigue sample cutting

Test samples for fatigue test cut from composites sheets were prepared with a certain dimensions according to the instrument manual specification [11] shown in Fig.(1).

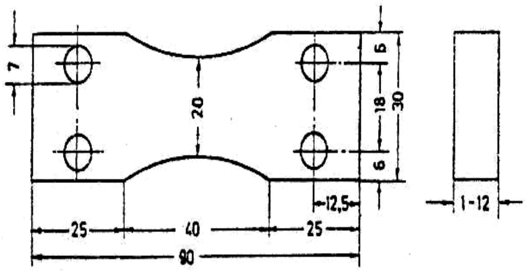


Fig.(1) Shape of fatigue test specimen with dimensions in mm.

Fig. (2) The samples of carbon fiber composites

Results and discussion

The fatigue testing is performed under constant applied load U=15 mm was done through out to obtaining σ-N curves. The tested samples show different behavior reflected on different regions of stress levels passing through prior to failure.

σ-N curves of epoxy specimen show the reduction in the first stage as show in Figure (3) and the deterioration will occur in specimen as second stage then finally the specimen fractured at $1*10^5$ cycle as shown in Figure (4).

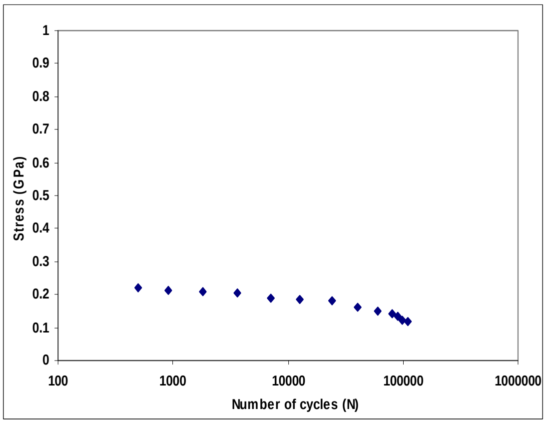


Figure (3) σ-N curves of epoxy specimen

Figure (4) The fracture in epoxy

σ-N curves of epoxy reinforced with 2.5 % carbon fiber is shown in Figure (5). Reduction in number of measured bending stress with increasing cycles number until reaching failure stage was observed. This can be attributed to the damage occurrence.

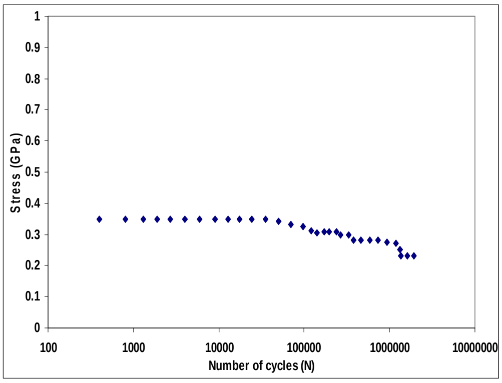
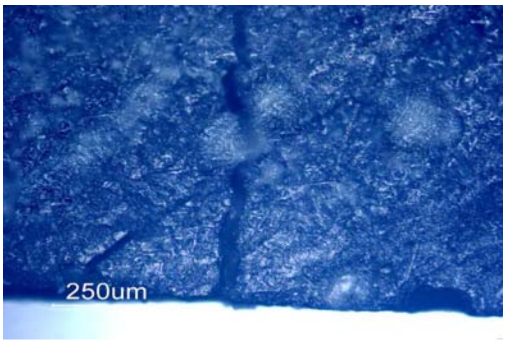


Figure (5) σ-N curves for EP-2.5% CCF

The process of damage starts off with the initiation of microcracks of matrix, which is an irreversible microdamage that occur throughout the stressed region at the waist of the test specimen manifested by microcracks. This can be regarded as a form of failure and is responsible for the subsequent failure mode by weakening of the fiber/matrix bonding and accounting for a progressive mode of failure termed pull out .Initiation of microcracks may be attributed to the low elasticity of the resin. Two factors appear to dominate delamination failure , the resin brittleness, and interfacial bonding[12].

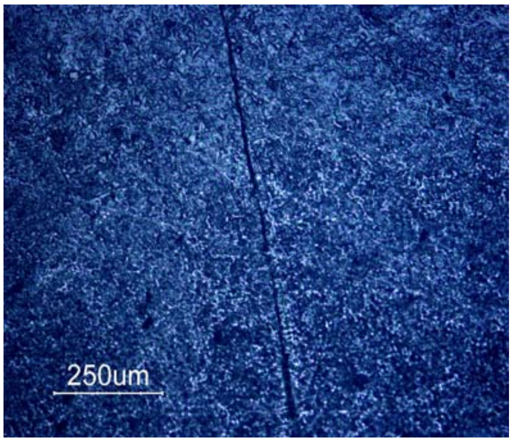
Examination of the samples by optical microscope, demonstrates that the composite with weight percentage 2.5% shows cracks in the sample and the width of crack is 5.3 μm which is shown in Figure (6).



Figure(6) Crack in EP-2.5%CCF

There was no fracture even after number of cycles $2*10^6$ (fatigue life).S-N curves for specimen with 2.5% wt chopped carbon fiber, shown in Fig.(5), show that the fatigue strength value is equal to 0.28 GPa at $1.2*10^6$ cycles and fatigue life were listed in Table (1) for all samples (The fatigue strength of a test specimen that can withstand a certain number of cycles without failure is evaluated), and no fatigue limit observed. (Fatigue limit is the stress level below which a material can be stressed cyclically for an infinite number of times without failure).

Optical microscope examination shows crack in the composites with 5% wt chopped carbon fiber and Figure (7) shows the crack in the sample, with width of 3.4 μm which is less than the crack width for specimen with 2.5% wt.



Figure(7) Crack in EP- 5% CCF

The values of fatigue strength, as well as the fatigue limit and the fatigue life increase and also no fracture is observed. It is clear that increasing the proportion of reinforcing has improved the fatigue behavior of the sample as shown in Table(1).(σ-N) curves show the reduction was observed in stress with the increase of the number of cycle as shown in Figure (8).

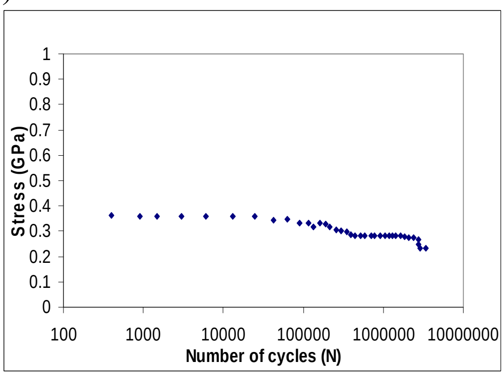
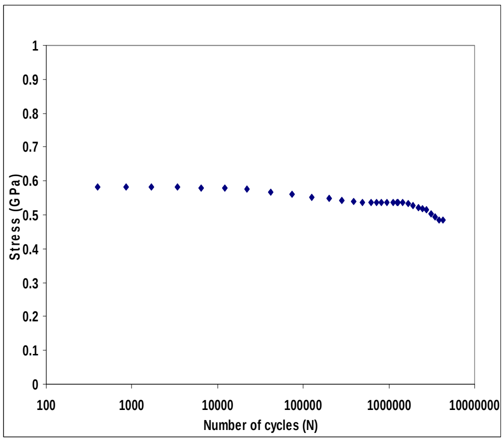
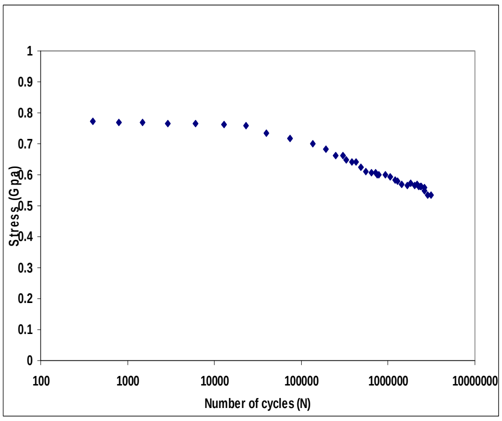


Figure (8) σ-N curves of sample test reinforced with 5 %CCF

No fracture or cracks were observed for the composites with 7.5%wt and 10%wt CCF, have high value of fatigue strength and fatigue limit as well as fatigue life, means that the composites suffer less damage during the course of fatigue test. This may be explained as the low surface density of chopped carbon fibers facilitate the penetration of matrix within fibers. The adhesion between fibers and matrix is strong enough to seize craze damages. The optical photographs show no sign of cracks generated. (σ-N) curves show in Figure (9).



(a) EP-7.5%CCF



(b) EP- 10%CCF
Figure (9) σ-N curves

The fracture was observed for the composites with 12.5% chopped carbon fiber (CCF) at approximately 10^5 cycle as shown in Figure (10). The photograph shown in Figure (11) reveals damage of fracture occurs because of the debonding of the fiber from the matrix, in some instant it is believed that fracture cracking debonding of the fiber/matrix interfaces will render the matrix unable to distribute stresses to the fiber, which results in reduced stiffness and different damping characteristics of the composite.[14]

The ability of the matrix to distribute stresses can change during fatigue loading, hence affecting the endurance limit of the composite. Density variations, due to either too little or too much resin, can have serious consequences for the composite. Too little resin results in inadequate bonding between fibers and the formation of voids. Too much resin lowers the weight percentage of fibers and increases the risk of cracks. When the bonds between fibers break ,crack will occur and then the fracture is happen. The weakest bonding between fibers is where voids and too much resin is located, when the sample subjected to fatigue loading , the weak bonding between the fibers can break, which reduces stiffness and buckling resistance.[13] Damage in fiber- reinforced composites can take many forms (1) fiber - matrix failure(2) fiber pull -out ,(3) fiber fracture.

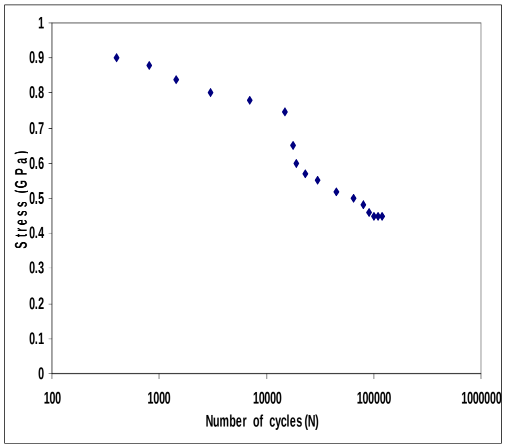


Figure (10) σ-N curves for EP-12.5% CCF

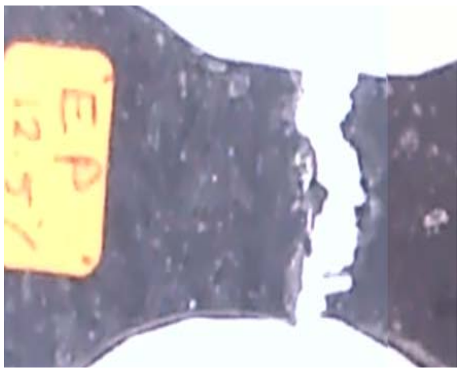


Figure (11) The fracture in EP-12.5%wt CCF

All EP composites with chopped carbon fiber composites show that σ-N curves deceased slightly as a result of the high stiffness properties of carbon fiber after high-cycle fatigue. High-cycle fatigue is associated with number of cycles greater than 10^5 cycles. Except the composites with 12.5%wt where it was fractured after low-cycle fatigue (low-cycle fatigue is less than 10^4 to 10^5 cycles).[15]

Composites materials exhibit very complex failure mechanisms under fatigue loading because of anisotropic characteristics in their strength and stiffness. Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals.[14] It is believed that the origin of fracture cracking is through microcracks produced by differential expansion effects attendant on cooling after moulding. Whether fracture occurs by tension and compression it was one or more of the following reasons:(i) cohesive failure of matrix; (ii) cohesive failure of the reinforcement; (iii) adhesive failure at the interface or interfacial region.

An idea of failure mode can be gained from the appearance of the fracture surface. if fracture takes place at an interface, then fibers were pull out with little or no polymer adhering to them (reinforcement failure).

Conversely, in matrix failure, the fiber will be pull out with polymer adhering to the fiber. In cases where there was strong interfacial bonding fiber fracture may be observed.[13]

Table (1) shows fatigue behavior for EP-chopped carbon fibers including maximum stress ,fatigue strength at two fixed number of cycles, fatigue life and fatigue limit. Maximum stress increase with increasing of chopped carbon fibers weight percentage as shown in figure (12). Highest fatigue strength was observed for the composites with 10% wt at $1.2*10^6$ Hz

Fatigue life and fatigue limit values increase with increasing of chopped carbon fiber weight percentage except the EP-12.5% wt CCF.

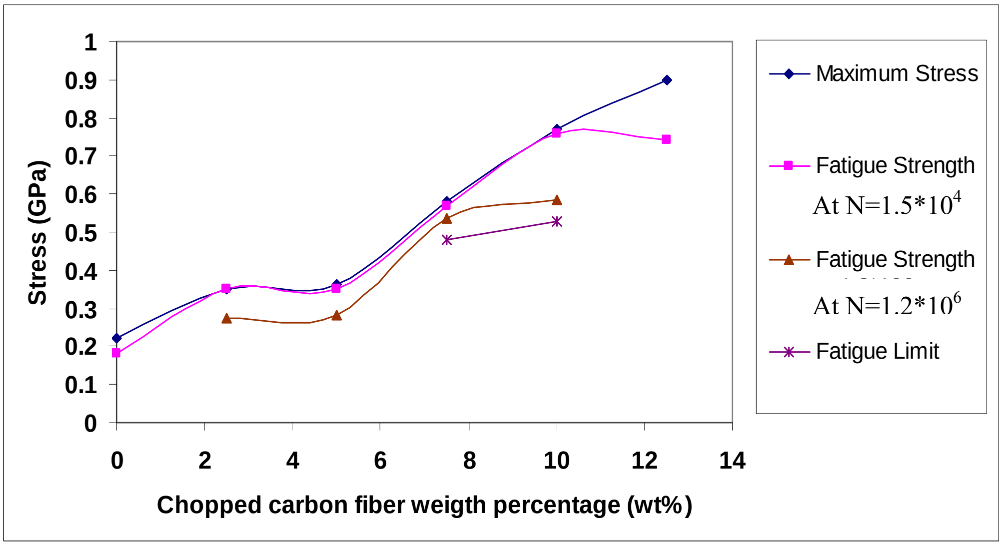


Figure (12) Variation of max. stress, fatigue strength and fatigue limit with wt% for CCF

Table (1) The values of fatigue behavior

Weight percentage	Maximum stress GPa	Fatigue strength σ_f at N=1.5*10^4	Fatigue strength σ_f at N=1.2*10^6	Fatigue limit GPa	Fatigue life
Epoxy	0.22	0.18 GPa	Fracture	……	$1.3 * 10^5$
EP-2.5%wt CCF	0.35	0.35 GPa	0.28 GPa	……	$2 * 10^6$
EP-5%wt CCF	0.37	0.35 GPa	0.29 GPa	……	$3.5 * 10^6$
EP-7.5%wt CCF	0.58	0.57 GPa	0.54 GPa	0.48	$4.2 * 10^6$
EP-10%wt CCF	0.77	0.76 GPa	0.59 GPa	0.53	$4.3 * 10^6$
EP-12.5%wt CCF	0.9	0.74 GPa	Fracture	…….	$1.2 * 10^5$

Conclusion

The results obtained out of this work lead to the following conclusions, reinforcing by chopped carbon fiber reduces the brittle nature of the epoxy resin as that its fatigue behavior is improved drastically.

The reinforcement of EP with chopped carbon fibers with different weight percentage increases the values of fatigue strength and fatigue life due to high strength of carbon fiber. Fatigue limit is observed only for two composites their with 7.5%wt and 10%wt.

However the specimen with 12.5%wt fracture at low-cycles fatigue due to the debonding of fibers from matrix. Which is characterized by the presence of two distinguished regions first is steady region and second region is leading to the deterioration region.

References

[1] B.Harris, H.Reiter, T.Adam, R.F.Dickson and G.Fernando 'Fatigue behaviour of carbon reinforced plastic' Composites. 21 (1990)No.3, PP.232-242.

[2] B.D.Agarwal, G.S.Giare 'Influence of the properties of the matrix material on the fracture toughness of short fiber composites' Material Science and Engineering. 52 (1982) No.1, PP.139-145.

[3] W.D.Callister *"Materials Science and Engineering"* (John Wily and Sons, Inc, New York, 2007)7th ed.

[4] T.M. Dicka, P.B. Jar, J.R. Cheng 'Prediction of fatigue resistance of short-fibre-reinforced polymers' International Journal of Fatigue. 31 (2009), PP.184-191

[5] S. Maiti, P. H. Geubelle 'A cohesive model for fatigue failure of polymers' Engineering Fracture Mechanics. 72 (2005), PP.691-708.

[6] T.A. Willway, R.G. White ' Optimization of CFRP laminate dynamic properties using combinations of short fibers and stiff/flexible resin matrices' Composites. 19 (1988) No. 3, PP.205-210.

[7] S.K. Garoushi, V.J. Lassila, P.K. Vallittu 'Short fiber reinforced composites: the effect of the fiber length and volume fraction' The Journal of Contemporary Dental Practice. 7 (2006) No.5, PP.1-10.

[8] J. Karger 'Effect of processing induced microstructure on the fatigue crack propagation of unfilled and short fiber-reinforced polyamide' Composites. 21 (1990) No. 3, PP.243-254.

[9] D. S. Saunders, T. J. Vanblaricum. 'Effect of load duration on the fatigue behaviour of graphite epoxy laminates containing delaminations' Composites. 19 (1988) No. 3, PP. 217-228.

[10] S.Kellas, J.Morton, P. T. Curtis 'The effect of hygrothermal environments upon the tensile and compressive strength of notched CFRP laminates, Part 2: fatigue loading' Composites. 21 (1990) No. 1, PP.52-62.

[11] K.J. Majeed ' Fatigue behavior of E-glass fibers/epoxy composites ' PhD thesis, College of Science, University of Baghdad, Baghdad, IRAQ (2005).

[12] S. Maiti, P.H. Geubelle 'Cohesive modeling of fatigue crack retardation in polymers: Crack closure effect' Engineering Fracture Mechanics. 73 (2006) PP.22-41.

[13] G.C. Mcgrath, D.W. Clegg, A.A. Collyer ' The mechanical properties of compression moulded reinforced reconstituted carbon fiber reinforced PEEK' Composites. 19 (1988) No. 3, PP.211-216.

[14] R. Unnporsson, M.T. Jansson ,T.P. Runarsson, NDT Methods for Evaluating Carbon Fiber Composites, Report of ICELAND Research Council, RANNIS, (2004).

[15] W. VanPaepegem, J. Degrieck ' Tensile and compressive damage coupling for fully reversed bending fatigue of fiber reinforced composites ' fatigue and fracture of engineering material & structure. 25 (2002) No. 6, PP.547-562.