THE EFFECT OF FIBER DIAMETER ON DEBONDING FORCE IN COMPOSITE MATERIALS AND THEIR INFLUENCE ON SOME MECHANICAL PROPERTIES +

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Abstract :

The present work is aiming to study the debonding force between fiber and matrix for different fiber diameters through pull out test technique where the fiber was embedded to a depth of (30)µm into the matrix . Kevlar 29 was selected as reinforcing fiber , and the tested diameters were (0.2, 0.4, 0.45, 0.5)mm, while the epoxy was of type Euxit 50 . In the second stage of this research a panel of (4)mm thickness, and of three densities, which were (3,4,and 5) fibers per centimeter , and the fiber reinforcement layer was located at the first third of the specimen thickness . Flexural, tensile, and fatigue tests were performed. The results showed that, in the pull out test , the base area of the fiber should be less than the side area , which affect the debonding force. Also the results of the flexural and fatigue tests for the unidirectional composite, showed that when the reinforcement layer was in the level of tension, the strength of the specimen increased by no less than 50%, in comparison with other case when the reinforcement was in the compression level , in addition to , the increase of the strength with the fiber density increase. The results of the tests can be implemented to determine the types and position of the reinforcement layers in the composite materials.

تأثير قطر الالياف على قوة الانفصال في المواد المركبة و انعكاسها على بعض الصفات الميكانيكية

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المستخلص:

البحث الحالي يهدف إلى دراسة قوى الفصل بين الالياف و الطور الأساس (Matrix) في المواد المركبة و لأقطار مختلفة من خلال تقنية سحب الليف (Pull out Test) حيث ان الليف غرز إلى عمق ٣٠ مايكرون ، الليف المستخدم كان من نوع (Kevlar 29) و بأقطار (0.2,0.4,0.45,0.5) ملم في حين أن الايبوكسي كان من نوع (Euxit 50) . تم تصنيع ألواح من المادة المركبة بسمك ٤ ملم و لكثافة ألياف هي (٣، ٤ ، ٥) ليف للسنتيمتر ، علما أن الألياف وضعت في مستوى ثلث السمك . لقد تم أجراء اختبار الشد و الانحناء

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الكلال . لقد بينت نتائج اختبار الشد أن المساحة السطحية الجانبية لليف يجب أن يكون اكبر من مساحة قاعدة الليف و التي ستؤثر على قياس قوة الفصل و كما بينت نتائج اختباري الانحناء و الكلال للعينات المدعمة بالألياف باتجاه واحد و في مستوى الشد هي اكثر بما لا يقل عن ٥٠% مقارنة مع تلك المدعمة في مستوى الانضغاط و كذلك هي تزداد بزيادة كثافة الألياف و يمكن الاستفادة من نتائج الاختبارات في تحديد أنواع و موضع التدعيم للطبقات في المواد المركبة

Introduction :

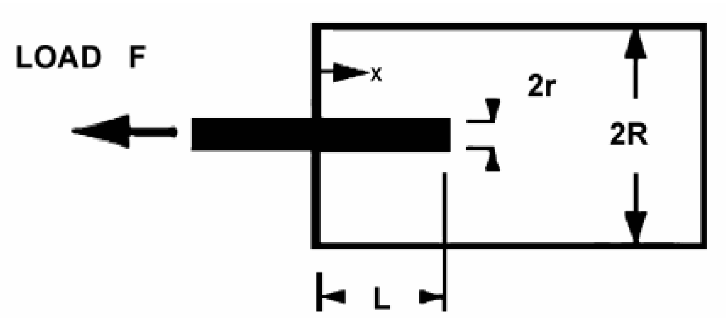
Over the years it has been well established that the strength and toughness of fiber-reinforced materials are determined to a great extent by the interface between the reinforcing fibers and the matrix. Extensive research has been carried out in order to understand the nature of the interfacial bond and to characterize its properties. A strong interface creates a material that displays exemplary strength and stiffness but that is very brittle in nature with easy crack propagation through the matrix and fiber. A weaker interface reduces the efficiency of stress transfer from the matrix to the fiber and consequently the strength and stiffness are not as high given the significance of the interfacial properties so it is not surprising that a large amount of research work has been carried out in the past twenty years on the characterization of the fiber–matrix interface. All of the approaches formulated have identified the so-called interfacial shear strength as the key parameter, which has been linked directly with the interfacial bond. There are four mainstream techniques for asses- sing the interfacial strength through single fiber testing; the single fiber pull-out test, the micro-debond test, the single fiber fragmentation test, and the micro-indentation test. The single fiber pull-out test shown schematically in Figure 1 has received considerable attention in recent years as a method of measuring the interfacial shear strength (IFSS) . There are several advantages of this test.

1 It is a direct measure of the quality of the adhesive bond between the fiber and matrix.
2- It requires only a small amount of fiber and matrix.
3- The pull-out test is not generally limited by the properties of the fiber and matrix.

This should be compared with fragmentation test where the failure strain of the matrix needs to be more than three or four times the failure strain of the fibers to meet the needs of achieving a saturated fragmentation state. The pull-out test can be carried out successfully with both brittle and ductile matrix system. Therefore, in the present study the single fiber pull-out test was used.[1]

General Theoretical Concept.

The pull-out experiment, which is believed to possess some of the characteristics of fiber pullout in composites, consists of a fiber or filament embedded in a matrix block or thin disk normal to the surface of the polymer (Figure 1). A steadily increasing force is applied to the free end of the fiber in order to pull it out of the matrix. Load and displacement are monitored as the fiber is pulled axially until either pull-out occurs or the fiber fractures. The strength of the fiber matrix interface can be calculated to a first approximation by balancing the tensile stress (σ_f) on the fiber and the shear stress (τ) acting on the fiber matrix interface, obtaining a relationship of the form $\tau=(\sigma_f/2)(d/L)$, where it is assumed that the shear stress is uniformly distributed along the embedded length and d is the fiber diameter. [2]



Figure(1): Schematic illustration of pull-out micromechanical test [2]

This energy can be measured with single fiber pull-out test which is based on pulling out a single fiber that is partially embedded in the matrix material. Measurement of energy absorption ability can also be defined as toughness of the material. Interface debonding and post- debonding friction are two important energy absorption mechanisms that occur during fiber/matrix interface failure in composite materials as a result of fiber pull-out (Figure 2). The size of absorbed energy depends on the fiber/matrix interface strength.

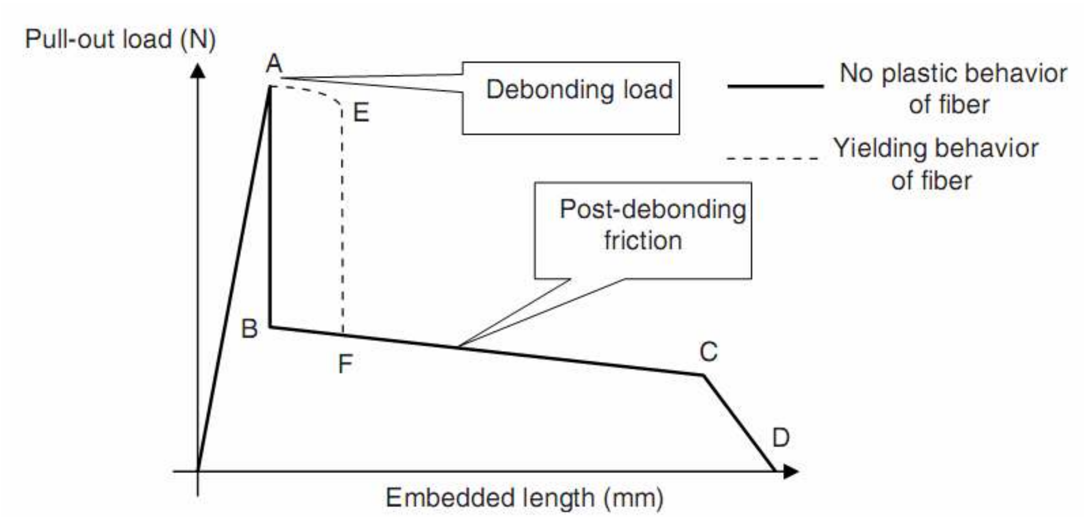


Figure (2):Typical pull-out load-displacement curve.[2]

During a pull-out experiment there are three possible failure modes of the fiber matrix interface :

(i) Failure may occur when the principal axial shear stress reaches the interface strength (t_{iu}), (which is the stress required to overcome the bonding force between the matrix and the fiber along the embedded length)which has a maximum absolute value at x=0, that is, at the surface where the fiber exits the polymer block.

(ii) Yielding at the interface might also occur if its yield strength t_{iu} is reached, in which case a constant shear stress distribution can be assumed along the embedded fiber length, as long as work hardening effects are negligible.

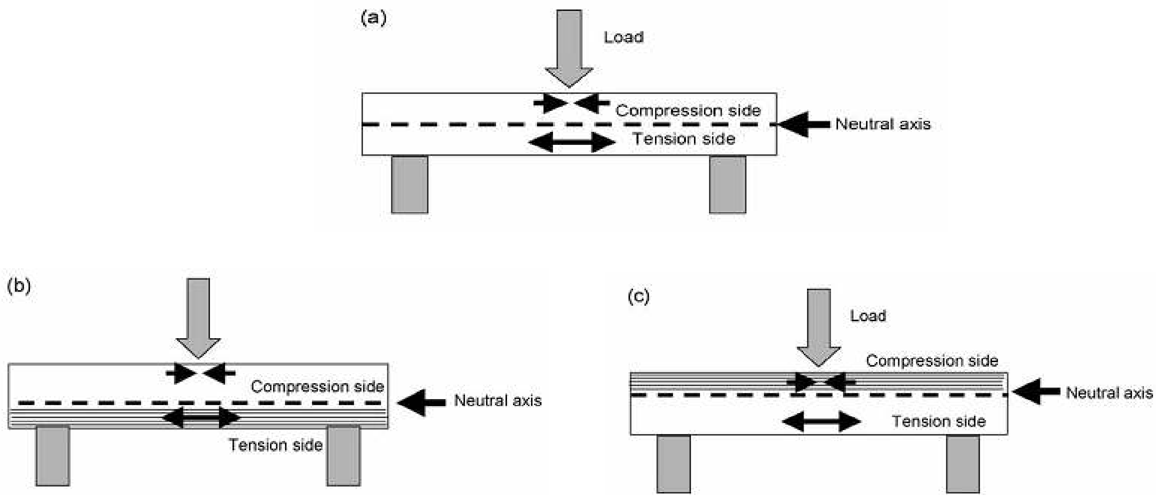
(iii) It has been observed experimentally that the mode of failure is sudden and catastrophic.

Since a stress concentration exists at the point where the fiber emerges from the matrix, this is the most likely point where failure initiates and rapidly propagates along the interface. Alternatively, energy approaches can also be used to analyze this test specimen where failure may occur if the interface fractures with work of fracture (G_i) per unit area of interface. The source of the required fracture surface energy is the strain energy stored within the specimen components. [3]

Investigation of the fracture strength and fracture mechanism of the fiber-matrix interface is extremely important because the mechanical properties of the fiber reinforced composites depend strongly not only on the properties of the fibers and the matrix but also on the fiber matrix interfacial ones. [4]

Another methodological matter is that the three point flexural strength and modulus are used as comparative values to evaluate differences between groups. In a homogenous polymer matrix test specimen, the neutral axis is located in the middle of the test specimen (Fig. 3a). However, the neutral axis is moved towards the fiber layer, when the test specimen consists of reinforcing fibers and a homogeneous polymer layer (Fig. 3b and c). When the reinforcing fibers are positioned on the compressive side of the test specimen, the neutral axis is moved close to the fiber layer and higher tensile stresses are exposed to the homogeneous polymer, which causes fracture of the test specimen at lower loads (Fig. 3c).

Depending on the ratio between the modulus of the fiber reinforcement and the homogeneous polymer layer, the neural axis location even inside the fiber layer, can cause the weaker polymer layer to be exposed to higher tensile stresses. [5]



Figure(3): Schematic representation of highlighting the areas of tensile and compression side.

If specimen is homogenous without any reinforcement, neutral axis located in the middle of test specimen (a), but if the fiber reinforcement is placed in tension side of the test specimen (b), or in the compression side (c), neutral axis is moved towards fiber reinforcement layer.[5]

Experimental Work

The scheme of this research is to work in two stages :

1- Single fiber pull out test to investigate the interface strength for fibers having different diameters and three types of epoxy covering (impregnation)

2- Bending and tensile tests , to investigate the relation between the interface strength and the toughness of the composite materials as well as studying the fatigue life according to the position of the fibers.

Aramid fibers of type Kevlar 29 was chosen as reinforcement , for their attractive mechanical properties , and importance of their uses . While for the matrix , epoxy type Euxit 50 (production of SwissChem)was selected for its wide range usage and specifications. The tensile test was performed on aramid fiber to ensure its mechanical properties , and it was according to the standard specifications , which were :

Table 1: Kevlar 29 technical specifications [6]

Density	1.44 g/cc	
Tensile Strength, Ultimate	2920 MPa	
	3620 MPa	Epoxy-impregnated
Elongation at Break	3.60 %	
Tensile Modulus	70.3 GPa	
Water Absorption	7.00 %	

While the matrix epoxy Euxit 50 technical data can be found at [7] .

In order to apply the single fiber pull out test an assembly was designed and implemented, it consisted of a frame holding a micrometer suitable to achieve an accuracy 0f (1) µm interval which allowed to indent the fiber in the matrix through the fixture, while the rig insure the horizontal level. The process of indention the fiber monitored through a 80x optical zoom video camera which connected to computer via interface card. specimen was of depth of (2)mm, and a diameter of (8) mm, as in fig.(4) . As mentioned earlier, the specimens were left in their places for 24 hours for solidification , then after seven days curing time, they were ready to be tested .

Figure (4): Schematic of the specimen

Figure (5): Pull out test specimens preparation assembly

The first stage was to change the fiber diameter , for the same embedded length which was (30) µm, diameters of (0.5, 0.45, 0.4, 0.2)mm were used , . While in the second stage , the embedded lengths were changed for the same fiber diameter, which was (0.5) mm. The second stage embedded lengths were (100, 150, 200, 250) µm , four specimens for each length were prepared . The pull out process was performed on the Gunt wp. 300 universal testing device. Load and extension recorded via data acquisition interface card which was prepared reach the accuracy range of one Newton. The specimens for tensile, bending and fatigue tests were manufactured with thickness of 4 mm and the fiber located at the first third of the thickness i.e. (1.33 mm), and the fiber density were 3, 4 and 5 fiber per centimeter.

For the bending test the specimens were cut to the dimensions of (4 x 16 x 85) mm, according to ASTM D790 standardization.This test was performed on the same universal tester, the test run for two cases the first one when the fiber in the tensile plan while the second run and the fiber in the compression plan. While for tensile test the specimens was performed according to ASTM D3039 standardization , the specimens were cut to (4 , 13 , 210) mm , with a gauge length of (140) mm [8] .

The fatigue test was performed on (HSM 20 - Alternating Bending Fatigue Device , by Hi-Tech education, Hampshire, England). The specimens dimensions were (4 ,10, 80) mm, as designated by the device manufacturer ,tests were made for the upper and lower thirds levels of reinforcement for one density which was (4 fiber / cm) , the test was for comparison between the fiber reinforcement position and interface or debonding influence on the failure of the specimens. The reinforcement layer was in dynamic tension , for several stresses to draw the S/ N curve for one group, while the other group of specimens , the reinforcement layer was put in compression.

Results and discussion

Four tests were performed , within this project and all the graphs were plotted via the (Golden Grapher 8) software .

Pull out test

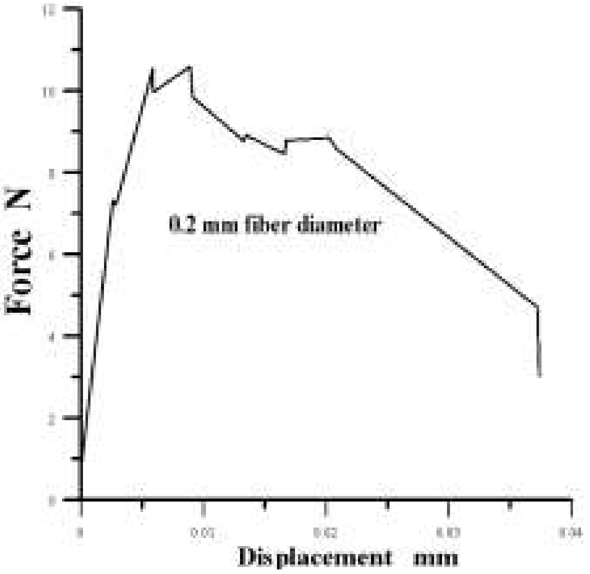
First of all , when the embedded length was fixed at 30 µm , the variables were the fiber diameter , which were (0.2, 0.4,0.45, 0.5) mm, the epoxy for impregnation which were Lyco 103, Quickmast 105 , and Euxit 50, , and the shape of the specimen a cylindrical and a sphere segment . The results are shown in table (2) .

Table (2): Pull out test results for the 30 µm embedded length

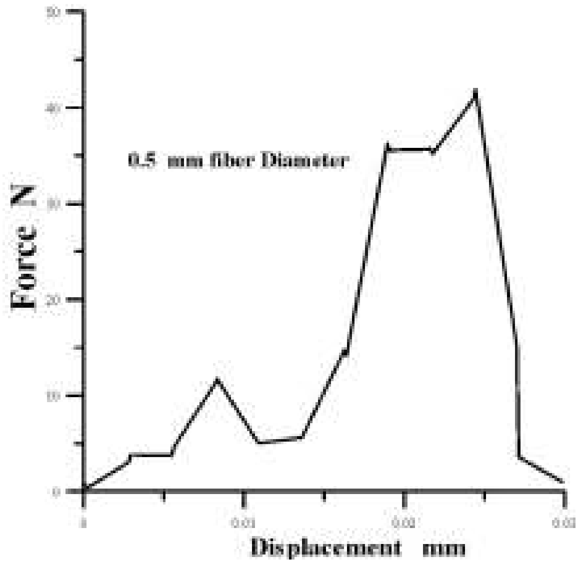
Item	Fiber dia. mm	Covering	Shape	Load First stage F_1 (N)	Load Second stage F_2 (N)	Embedded Length µm	A_S/A_B	F_1/F_2
A4C	0.4	Lyco 103	C	11.15	22.16	30	0.3	0.50
E1C	0.4	Euxit 50	C	10.1	33.12	=	=	
A2C	0.45	Lyco 103	C	15.75	30.8	=	0.267	0.65
B1C	0.45	quickmast105	C	16.1	24.8	=	=	0.64
E2C	0.45	Euxit 50	C	10.65	38.5	=	=	
B2C	0.5	quickmast105	C	13.21	66.34	=	0.21	0.199
A5C	0.5	Lyco 103	C	10.68	35.82	=	=	0.298
E5C	0.2	Euxit 50	C	7.2	10.7	=	0.67	

Note : The designation of the specimen is : **A, B, E** for the epoxy matrix , **x** for number of the specimen, **C** , cylindrical shape specimen

An important point emerged which was that as the diameter of the fiber was relatively large , so with the embedded lengths were very small in this aspect an interesting fact was quite clear , which is that the base area , (if the embedded segment of the fiber was to be resembled to a cylinder) is significantly large in comparison to the side surface area , where all the debonding should take place , that means that the debonding force of the side area is much less than the base detachment from the matrix epoxy force , which is clear in the load - distance graph of the pull out test in the specimens results . While this feature was not quite clear for the curve of the pull out test for the fiber of 0.2 µm diameter , as in fig. (6).



A



B

Fig (6) : Pull out test curves for , A \(0.2 mm), B \(0.5) mm fiber diameter

Table (3) shows the results of the pull out test for various embedded lengths, but ,with the same fiber diameter of (0.5) mm, and epoxy matrix, which was (Euxit 50).

Table (3): Pull out test results , for various embedded lengths

Item	Diameter of Fiber MM	Covering	Embedded length µM	Stage one Load F_1 (N)	Stage two Load F_2 (N)	A_S/A_B	F_1/F_2
E11C	**0.5**	**Euxit 50**	**100**	**13.2**	**37.4**	**0.8**	**0.22**
E21 C	**=**	**=**	**150**	**-**	**51.2**	**1.2**	**-**
E31C	**=**	**=**	**200**	**-**	**67.8**	**1.6**	**-**

Note : The designation of the specimen is : **E** for the Euxit 50 epoxy matrix , , **C** cylindrical shape specimen.

Fig (7), shows the relation between the embedded length and the force of the debonding for the aramid fiber used that was of 0.5 mm diameter, the empirical equation deduced was in the form

$$y = 0.0012x^2 + 0.078x - 0.3467$$

where y represent the force , and x represent the embedded length , the regression factor is R = 0.901 , which is quite acceptable.

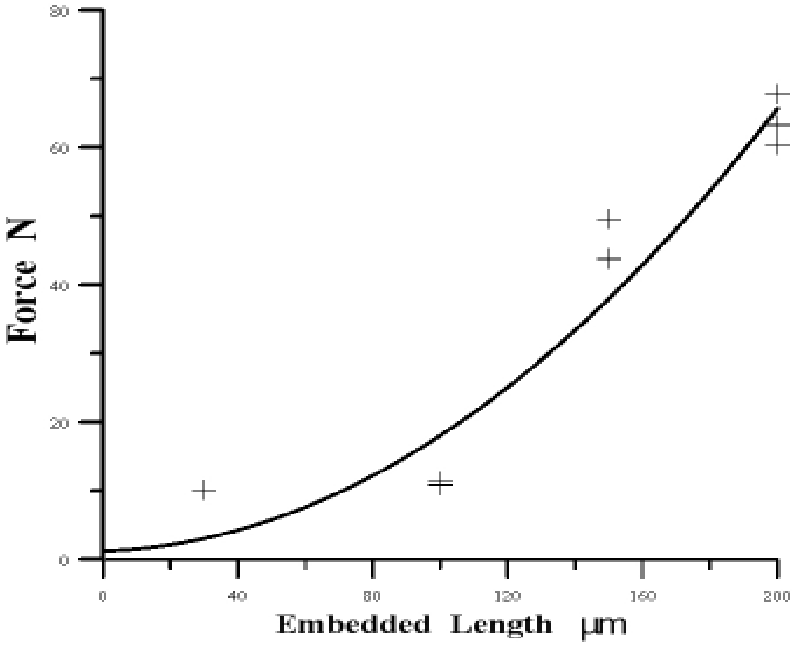


Fig (7): Shows the relation between the embedded length and the force of the debonding for the aramid fiber.

Bending test results

The results in table (4), shows, that when the reinforcement is in the lower third the strength is greater than in the other case even when the least fiber density down with the highest fiber density up .The limited increase of the strength when the reinforcement in the compression plane , can be explained that each fiber and the surrounding interphase acts micro semisolid tube , which enhance the bending strength of the specimen [8].

Table (4): Pending test results

Density &position	Bending Stress N/mm^2						Average
3 fibers/ cm Lower third	52.46	54.293	59.63	62.73	68.92	46.6	**57.4388**
3 fibers/ cm Upper Third	34.343	36.38	39.48	48.25	56.11		**42.913**
4 fibers/ cm Lower third	50.33	53.62	84.33	80.09	104.54		**74.744**
4 fibers/ cm Upper Third	34.5	41.27	42.7	70.45			**47.23**
5 fibers/ cm Lower third	99.6	100.7	102.62	107.12	123.52		**106.712**

Most of the tested specimens , failed without breaking up into two or more pieces due to the strong bonding between the matrix and the fibers , even for the relatively weaker specimens of the lowest density at the upper third position , which interestingly closer in the toughness value to the specimens without reinforcements as shown in figure (8)

While the relation between the bending stress and the fiber density is shown in figure (9)

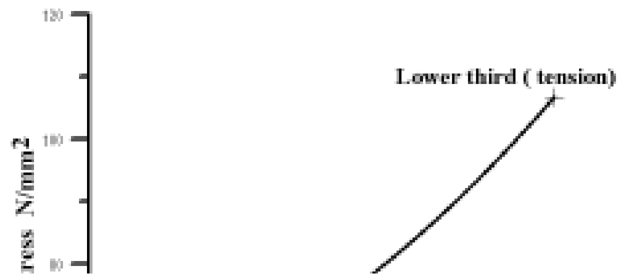


Figure (8): Failed bending specimens

Figure (9): Relation between the bending stress and the fiber density

Tensile test results

The increase of the stress with the density of the fiber is not linear, as in figure (11) which explain the relation between the strength with density of the fiber and how an increase of (1 fiber/cm) affected the ultimate tensile stress. The empirical equation for that relation was

$Y = 23.34 + 1.8475 * X + 0.9275 X^2$ while $R^2 = 0.985998$

The results of tensile stress are shown in table (5).

Table (5): Tensile stress results

Density fiber/cm	Force kN	Stress N/mm^2
3	1.875	36
3	2.00	38.46
4	2.37	45.57
5	2.85	54.8
5	2.95	56.73

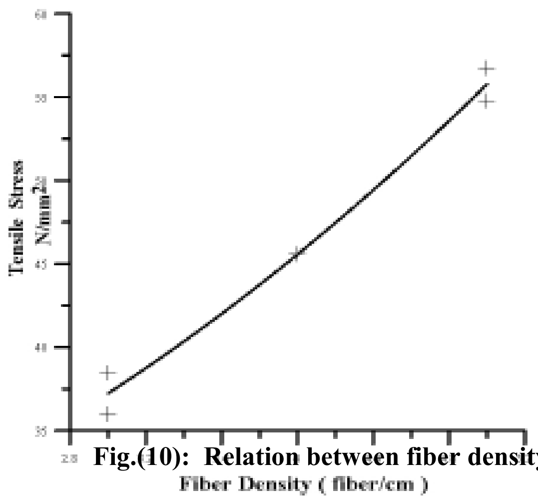


Fig.(10): Relation between fiber density and ultimate tensile stress

Fatigue test results

Several specimens of the density of (4 fiber / cm) were tested into two groups , one for the tension position of the reinforcement layer that is at the upper third of the specimen, While the other for the reinforcement layer in compression position , which means the reinforcement was at lower third of the specimen, the results are shown in fig (11) . For all specimens the failure (crack) was initiated within the two thirds of the specimens other than the reinforced , and grew very fast as in brittle materials , but stopped or resisted by the reinforcement layer. While it is worth to note the used polymer based material ha no apparent endurance limit.

Figures (11), and (12) show the fatigue curves for the cases of the fiber reinforcement in compression and tension, that is , in the lower or upper thirds respectively, while the respective empirical equations and the regression factors were:

$$\ln(Y) = -0.4756847806 * \ln(X) + 9.968815707 \qquad R^2 = 0.868289$$

$$\ln(Y) = -0.1869365071 * \ln(X) + 5.598064482 \qquad R^2 = 0.948197$$

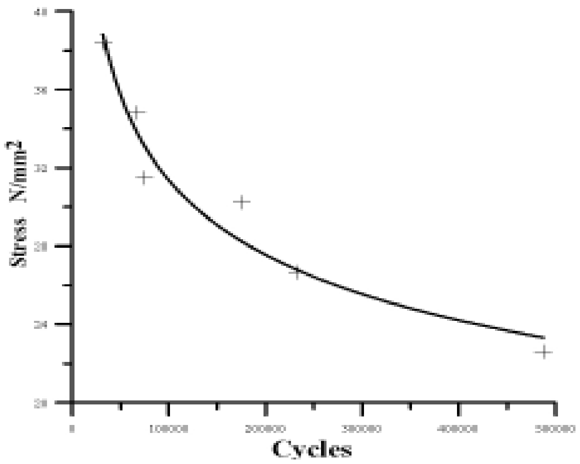


Fig. (11): Fatigue curve for the case of the reinforcement in compression

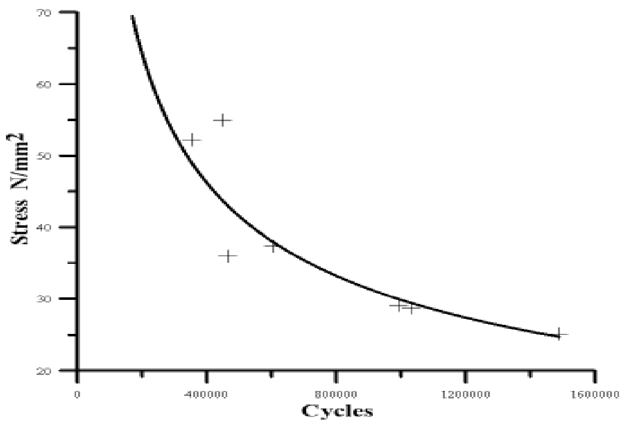


Fig. (12): Fatigue curve for the case of the reinforcement in tension

Conclusions:

1- The ratio of the diameter of the fiber to the matrix diameter in the pull out specimen , used in this work was 1/ (15 – 20) as reached by previous works , and it was quite acceptable , but with yarn as reinforcement , may be other ratio would be better resembling
2- In the pull out test the side surface area of the fiber should be well greater than the (base) area , that is to coordinate between the fiber diameter and the intended embedded length, to further marginalize or annul the force needed to detach the fiber from the matrix , when debonding occurs all along the embedded length and only the (base) is still to be (stripped).
3- Pre-impregnation with the same matrix epoxy or with another compatible type of epoxy , would enhance further the fiber matrix bonding , but it should be carefully managed , in order not to make the interphase brittle.
4- Bending and Fatigue tests for unidirectional reinforcement, showed that fiber reinforcement in a tension position was stronger by no less than 50% , from compression position , which presumably also applicable to the poisoning of the laminated composite materials.

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