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Types of the Fiber Glass-Mat on Fatigue Characteristic of Composite Materials at Constant Fiber Volume Fraction: Experimental Determination

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Abstract

The aim of this work is to study the influence of the type of fiber glass –mat on fatigue behavior of composite material which is manufactured from polyester and E-glass (woven roving, chopped strand mat (CSM)) as a laminate with a constant fiber volume fraction (VF) of 33%. The results showed that the laminates reinforced with E-glass (woven roving) [0/90, ±45.0/90] and [0/90, CSM, 0/90] have lower fatigue strength than the laminates reinforced with E-glass $[0/90]_3$,$[CSM]_3$ and [CSM, 0/90, CSM] although they had different tensile strength; the best laminate was $[0/90]_3$.

Keywords: *composite material, Fatigue, Fiber glass mat.*

1. Introduction

Composite materials are commonly discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and is called the reinforcement; whereas the continuous phase is usually softer and is termed the matrix. The matrix holds the reinforcements in an orderly pattern [1]. This work focuses on fiber-reinforced composites composed of fibers embedded in a matrix; the fibers are long, continuous in one or multiple directions. Such materials offer advantages over

Conventional isotropic structural materials such as steel, aluminum and other types of metal. These advantages include high strength, good fatigue strength and corrosion resistance. In addition, by changing the arrangement of the fibers, the properties of the material can be tailored to meet the requirements of a specific design [2].

Z. Hashin and A. Rotem [3] studied the influence of off-axis loading on fatigue strength of fiber glass – epoxy unidirectional composite; fatigue curves are shown for off-axis angles of 0, 5, 10, 30 and 60 degrees. Even small off-axis angle of 5 to 10 degree cause a drastic reduction in the fatigue strength compared with 0 degree loading. With the off-axis angle of 60 degrees, the fatigue strength at 10^5 cycles to failure decreased to about 2.5kg/mm^2 from a value of about 80kg/mm^2 at 0 degree orientation.

Wedad Al-Azzawy[4] studied the fatigue and vibration characteristics of laminated composite shells of revolution. All tests were conducted at room temperature (18-25c^o).The aim of fatigue test is to determine (S-N) curves of 0, 45, 90 degree under stress ratio R=-1. The S-N curves showed fatigue strength at 10^6 cycles, of about, 117MP$_a$, 17MPa and 12MPa at 0, 45 and 90 degree orientation respectively.

Muhannad Z. Khalifa, et.al [5] studied the fatigue behaviors of composite material manufactured for this paper by stacking four layers of E-glass fiber in different angle orientations [0, ±45, 0/90] degree immersed in polyester resin with total thickness 4mm. The results showed that failure of laminas at ±45, and, 0/90 degree is due to matrix failure in the direction of fiber, whereas for unidirectional lamina at 0 degree the failure is due to fiber breakages.

Al-Alkawi, et.al [6] studied the influence of temperature on the ultimate tensile strength (UTS) of composite material which is manufactured from polyester and E-glass (woven roving, chopped strand mat) as a laminate with a constant fiber volume fraction (VF) of 33%. The results showed a little effect of temperature on tensile strength in the range of room temperature (RT) to 50 ^{o}C for laminates reinforced with E-glass (woven roving) [0/90, ±45.0/90], $[0/90]_3$, and [0/90, CSM, 0/90], but for laminates reinforced with E-glass chopped strand mat (CSM), as $[CSM]_3$ and [CSM, 0/90, CSM], a continuous reduction in strength was observed with increasing temperature from (RT) to 60 ^{o}C. The highest percentage reduction in strength was 23% at 60^{o}C as compared to (RT) for $[CSM]_3$ laminate.

2. Experimental Work

2.1. Materials

In this work, E-Glass fiber which was obtained in the form of discontinuous and continuous woven strand mats is used. It was not possible to measure the glass fiber properties experimentally, hence reasonable values were chosen from the literature. Polyester (TOPAZ-1110 TP) unsaturated resin with1.5% hardener was used for the matrix. Table (2-1) shows the composition of glass fibers and Table (2-2) shows some of the reported properties of E-glass fibers and Polyester found in the literature seems to vary according to their manufacturing source.

Table 2-1 ,
Composition of Glass Fibers: [7].

Material	Silicon dioxide	Aluminum Oxide	Boric Oxide	Sodium Oxide and potassium Oxide	Magnesium Oxide	Titanium dioxide	Iron Oxide	Iron	Calcium Oxide
E-glass (range %)	52 to 56	12 to 16	5 to 10	0 to 2	0 to 5	Up to 1.5	0 to 0.8	0 to 1	16 to 25

Table 2-2,
Mechanical Properties of Fiber Glass And Polyester (Resin) [7].

Material	Density g/cm3	Modulus of elasticity (GPa)	Strength (MPa)	Poisson's ratio
E-glass	2.54	72.4	3450	0.2
polyester	1.1-1.4	2.1-3.4	34.5-103	0.37-0.4

2.2. Manufacturing Processes (Hand Lay-up)

The choice of a manufacturing process depends on the type of matrix and fibers. Hand lay-up is the simplest and oldest open molding method of the composite fabrication processes, Laminate panels were prepared according to ASTM D5687 [8], and the following stages of preparation were used:

1. The mould, which was made of a thermal glass plate 60*80cm^2, was cleaned and treated with a release wax in order to prevent the finished product from sticking to the frame. The liquid resin was mixed with 1.5% hardener and applied over the wax.
2. The first layer of reinforcing material (45*75cm2 woving roving mat) was laid over the resin while it was still wet; it was embedded into the resin and completely wetted with a stiff brush.
3. Any air bubbles trapped under the reinforcement were removed by working them out to the edge using special rollers.
4. The application of additional layers (3 layers) of fibers and resin was repeated to produce the final laminate [CSM]3, [0/90]3, [0/90, ±45, 0/90], [CSM, 0/90, CSM], [0/90, CSM, 0/90] with a constant volume fraction of about 33%.
5. A heavy weight was applied on the cover of the mould giving a pressure of 4135 N/m2 to prevent buckling during curing.

6. The laminate was left in the mould to cure for 24 hours at room temperature.
7. The laminate was trimmed to remove excess resin.
8. The product laminate was left 3 hours in oven at 60oC in order to be sure that the curing process was achieved.
9. The part was ready to be cut into specimens; it was left 3 weeks before testing was carried out.

2.3. Specimen Preparation

The specimens were cut out of 40*70 cm^2 panels and followed by polishing the cut edges in two stages in order to remove flaws and to obtain smooth and crack-free surfaces. Silicon carbide paper of grade 400 and 800 was used for this purpose.

2.4. The Tensile Test Specimens

2.4.1. Matrix

In order to find the mechanical properties of the matrix, tensile specimens were prepared according to ASTM D 638-97 [9] as shown in Figure 2-1.

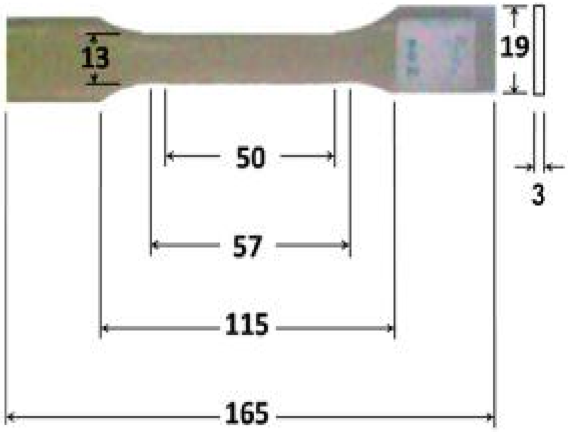

Fig. 2-1. Polyester Tensile Test Specimen, (Dimensions are in mm). [9].

2.4.2. Composite Material

Tests specimens were designed according to ASTM D3039 standards [10] as shown in Figure (2-2).

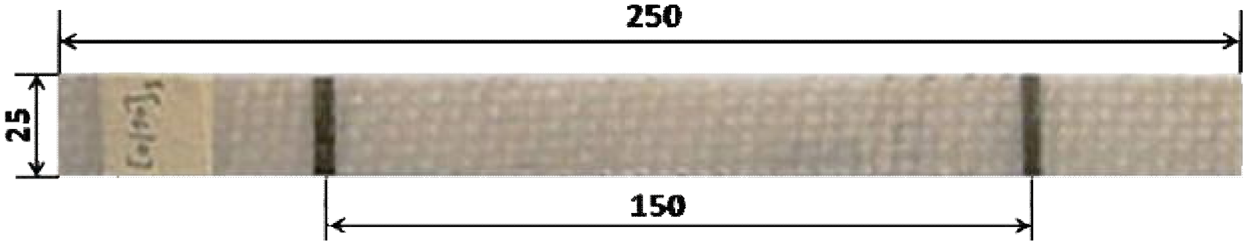

Fig. 2-2. Composite Tensile Test Specimen (Dimensions in mm).

2.4.3. Tensile Tests Procedure

The tensile tests were performed in a Tinius Olsen (H50KT) test machine at room temperature. The maximum load capacity of the test machine is 5 ton. Figure (2-3) shows the specimen clamped securely in the fixture before applying the load. A constant speed of 1 mm/min was used during the test until specimen failed [10].

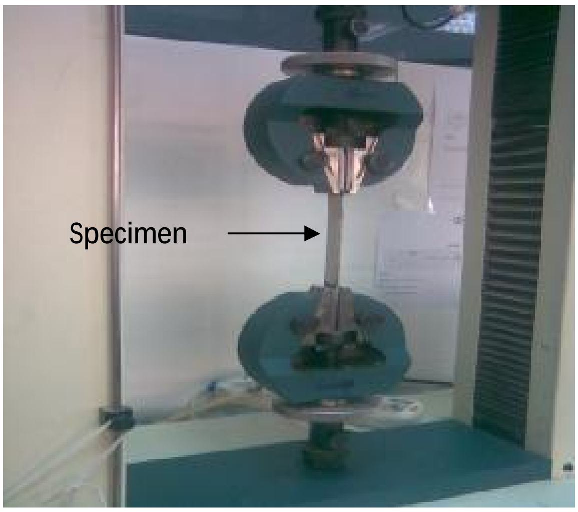

Fig. 2-3. Close Up of Specimen Fixture.

The test results show that different fracture modes observed like brittle fracture of the matrix and breaking of the fibers gradually depending on the type of layers used in laminates. Figure (2-4) shows some examples of tensile test specimens after failure.

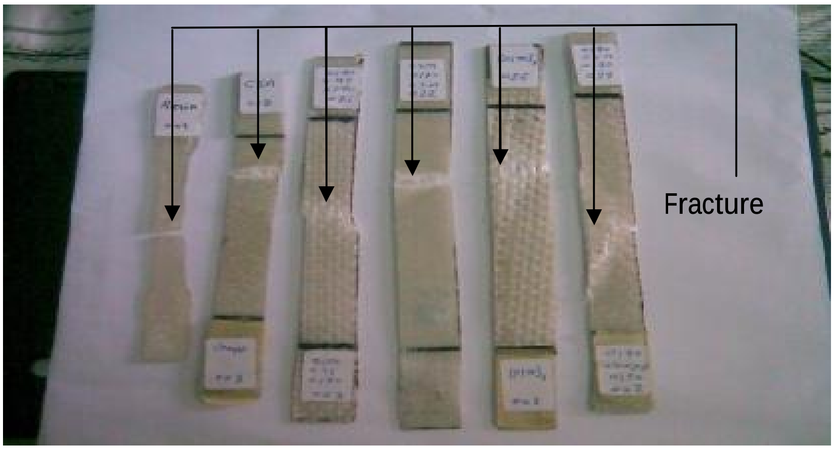

Fig. 2-4. Examples of Tensile Specimens after Failures.

2.5. Fatigue Test Specimens Preparation

The specimens were prepared according to ASTM D 3479/D 3479M–96, standard test method for fatigue of polymer matrix composite materials [11].

Fatigue specimens were cut in suitable dimensions to satisfy the machine test section that suited for flat plate specimens. Figure (2-5) shows the shape and dimensions of fatigue specimen [12].

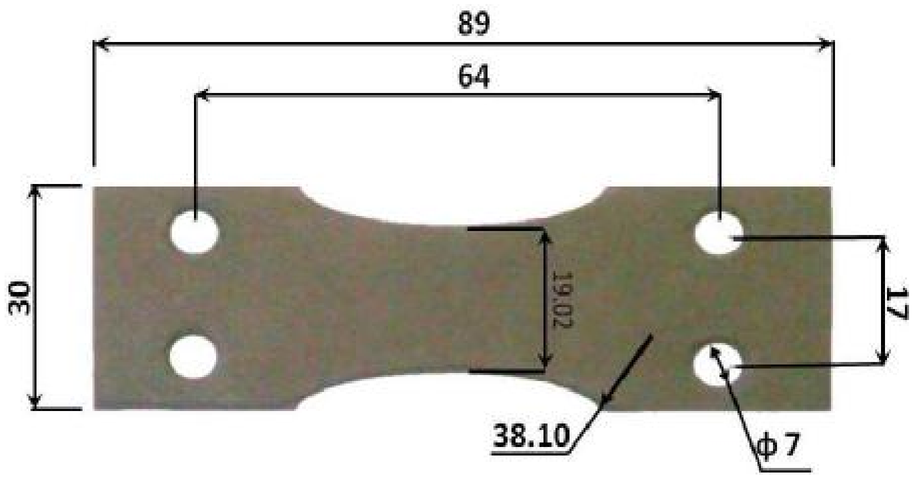

Fig. 2-5. Fatigue Specimens (all Dimension in *mm*) [12].

2.5.1. Fatigue Tests Procedure

The type of fatigue test is a cyclic bending loading procedure. The purpose of the test is to generate S-N data (stress vs. number of cycles) for each specimen of laminate at room temperature. The AVERY Fatigue Testing Machine Type-7305 was used to apply reverse loads as shown in Figure (2-6). Grips are provided for the bend test where the load is imposed at one end of the specimen by an oscillating spindle driven by means of a connecting rod, crank, and double eccentric attachment. The eccentric attachment is adjustable to give the necessary range of bending angle. The applied stress is calculated from the deflection. A revolution counter is fitted to the motor to record the number of cycles. The cycling rate is 1400 rpm [12].

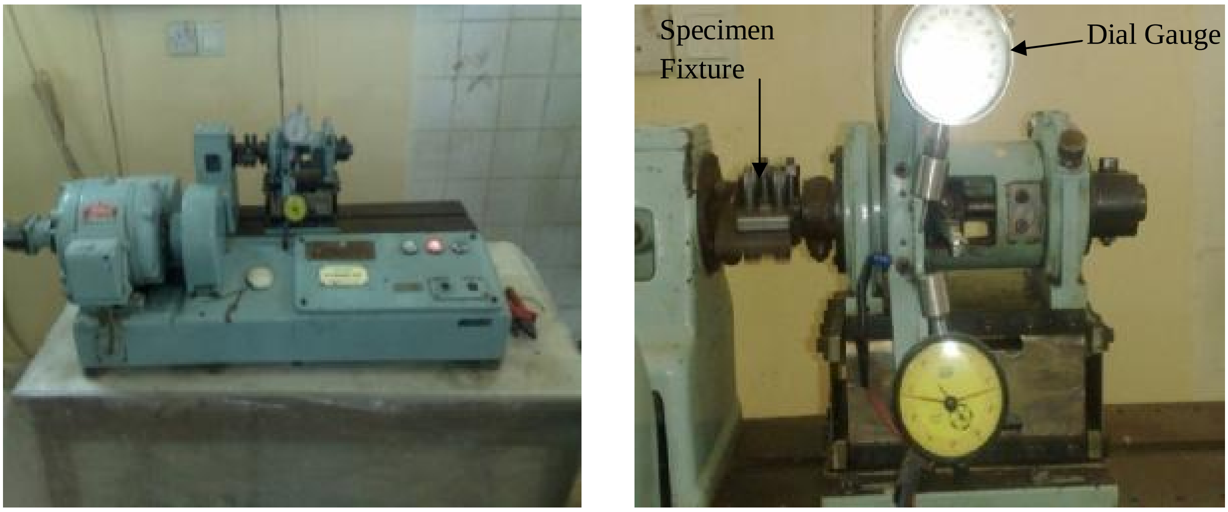

Fig. 2-6. a) AVERY Fatigue Testing Machine Type 7305, b) Close up of Specimen Fixture.

The machine was adjusted at stress ratio R= -1. A series of experiments were performed on each set of specimens by changing the deflection angle each time and recording the number of cycles to failure. Examples of some specimens after fatigue test failure are shown in Figure (2-7).

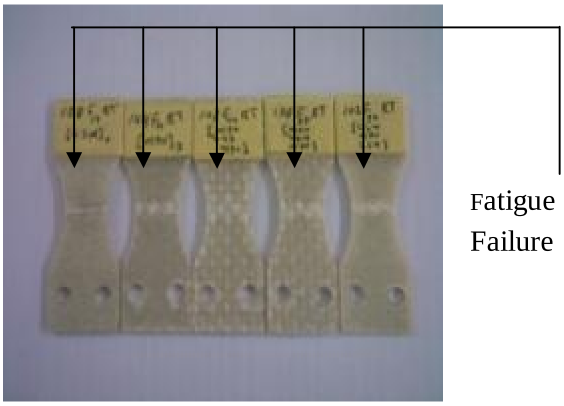

Fig. 2-7. Fatigue Failure of Composite Specimens.

Fatigue damage in the composite is initiated by the formation of transverse matrix cracks, due to the presence of higher stress concentration and induce localized ply delamination. As the fatigue cycling continues, matrix cracks and ply delamination grows and cause weft fiber bundles (at 90^o to loading direction) to split and fracture setting the stage for final fracture.

3. Experimental Results and Discussion

3.1. Tensile Test Results

Table 3-1 shows the experimental tensile strength of the matrix at room temperature (RT).

Table 3-1,
Tensile Test for Matrix (Polyester) at (RT).

No.	Matrix , Resin	specimens			Ultimate tensile stress (UTS)MPa			Average UTS MPa
1	Polyester,TOPAZ 1110	1	2	3	33.38	31.75	32.59	32.567

Table (3-2) shows the same results for fibre strengthened composite material at room temperature and under the same volume fraction of fibre(about 33%) with different laminates (3 layers of different fibre orientation). It can be observed that regardless of the orientation of the fibres, the addition of the fibres contributes to strengthening of the composite. However, the $[0/90]_3$ and [0/90, CSM, 0/90] orientations yield the highest strengthening in the range of 7.32 to 7.64 times the strength of the original matrix. Strengthening of the other three fibre orientation,

$[CSM]_{3,}$ [0/90, ±45, 0/90] and [CSM, 0/90, CSM], is only in the range of 4.04 to 4.64 times the strength of the original matrix. Elastic modulus (E) was calculated by constructing a secant between two points, typically at strain values of 0.001 and 0.003 [10].

Table 3-2,
Tensile Tests for Composite Materials at (RT).

No.	laminate description	Specimens No.			UTS , (MPa)			UTS_{ave}(MPa)
1	$[CSM]_3$	4	5	6	142	142.5	147.5	144
2	[0/90,±45,0/90]	7	8	9	155	121	119	131.667
3	[CSM,0/90,CSM]	10	11	12	155	123.3	173.5	150.6
4	$[0/90]_3$	13	14	15	256.7	240	250	248.9
5	[0/90,CSM,0/90]	16	17	18	221	249.5	245	238.5

3.2. Fatigue Test Results

Tables (3-3) to (3-7) show fatigue test results at constant amplitude loads for laminates $[CSM]_3$, $[0/90]_3$, [0/90,±45, 0/90] , [0/90, CSM, 0/90] and [CSM, 0/90, CSM] respectively. The S-N curve was obtained from these results as shown in Figure (3-1). The equation of power law regression is given by [13]:

$$\sigma = aN^b \qquad \dots \ (3.1)$$

Where (. is the applied stress amplitude, and (***a***), (***b***) are the fitting parameters. The regression constants representative of the fatigue trends, from the model, and the fatigue strength limit at 10^7 cycles are given in Table (3-8).The fatigue strength for the laminates to their tensile strength is 0.545, 0.379, 0.203, 0.15 and 0.418 for $[CSM]_3$, $[0/90]_3$, [0/90, ±45, 0/90] , [0/90, CSM, 0/90] and [CSM, 0/90, CSM] laminate respectively. The higher fatigue strength is 94MPa for laminate $[0/90]_3$ and the lower fatigue strength is 26.7MPa for [0/90, ±45, 0/90] laminate. Then it can be observed that the orientation of fiber glass-mat has strong effect on the fatigue strength of these laminates. These results are in agreement with finding of Z. Hashin [3] and Wedad Al-azzawy [4].

Table 3-3,
Fatigue Results for Laminate $[CSM]_3$.

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
19, 20, 21	128	60000, 50000,55000	55000
22, 23, 24	116	360000, 406000, 380000	382000
25, 26, 27	103	900000, 989000, 850000	913000
28, 29, 30	90	1150000, 1220000, 1380000	1250000

Table 3-4,
Fatigue Results for Laminate $[0/90]_3$.

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
31, 32, 33	144.5	18000, 16000, 20000	18000
34, 35, 36	130	296000, 332000, 420000	349000
37, 38, 39	115.5	792000, 820000, 920000	844500
40, 41, 42	101	1080000, 1200000, 1350000	12١0000

Table 3-5,
Fatigue Results for Laminate [0/90, ±45, 0/90]

Specimens No.	Applied stress amplitude (MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
43, 44, 45	111	20000, 25000, 15000	20000
46, 47, 48	99.5	31500, 24500, 28000	28000
49, 50, 51	88.5	50500, 59000, 69000	59500
52, 53, 54	77.5	78000, 86000, 101500	88500
55, 56, 57	55.5	400000, 350000, 450000	400000

Table 3-6,
Fatigue Results for Laminate [0/90, CSM, 0/90.

Specimens No.	Applied stress amplitude (MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
58, 59, 60	156	5000, 5500,4500	5000
61, 62, 63	140.5	6500, 7000, 7500	7000
64, 65, 66	124.5	21000, 17500, 18500	19000
67, 68, 69	109	53000, 70000, 60000	61000
70, 71, 72	75	273000, 301000, 364000	312700
73, 74, 75	58	400000, 450000, 515000	455000

Table 3-7,
Fatigue Results for Laminate [CSM, 0/90, CSM].

Specimens No.	Applied stress amplitude (MPa)	number of cycles to failure (NF)	$(Nf)_{ave.}$
76, 77, 78	102.5	90000, 110000, 160000	120000
79, 80, 81	92.5	580000, 610000, 671500	620500
82, 83, 84	82	1250000, 1430000, 1580000	1420000
85, 86, 87	72	1520000, 2360000,2150000	2010000

Table 3-8,
Fatigue Parameters and Fatigue Strength for Laminates.

laminate description	a	b	Fatigue strength at 10^7 cycles (MPa)
$[CSM]_3$	388.848	-0.09921	78.579
$[0/90]_3$	296.738	-0.071088	94.353
[0/90, ±45, 0/90]	1050.55	-0.2278	26.718
[0/90, CSM, 0/90]	841.735	-0.1959	35.799
[CSM, 0/90, CSM]	398.75	-0.1138	63.694

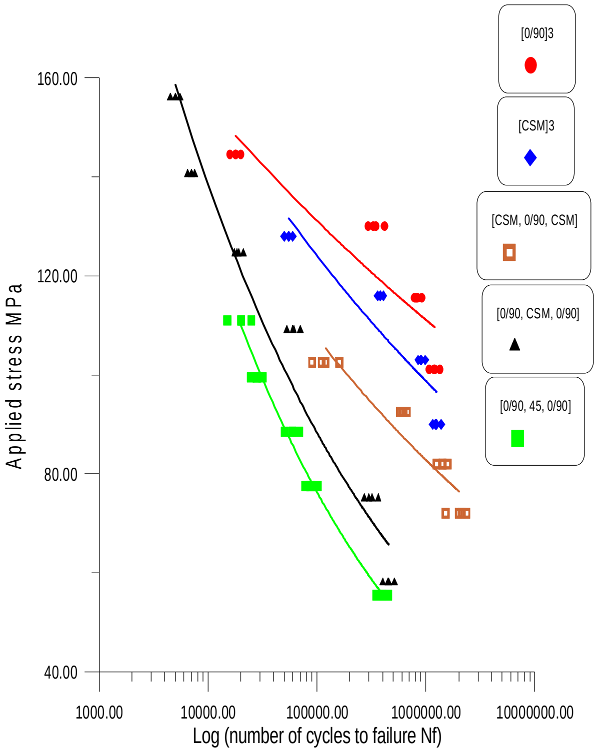

Fig. 3-1.S-N curve for all Laminates Used in This Study.

3.3. Improvement Factor

3.3.1. Strength Improvement Factor (SIF)

Several factors are responsible for the improvement in strength: volume fraction of fiber, type of fiber, orientation of fiber, type of matrix. Therefor the laminates used in this study were manufactured from the same matrix and same fiber under the same volume fraction of fibers by using different type of fiber glass mat (chopped strand mat, woving roving mat). Table (3-9) shows strength improvement factor (SIF) for laminates $[CSM]_3$, $[090]_3$, [0/90, CSM, 090], [CSM, 0/90, CSM], [0/90, ±45, 0/90] based on the laminate [0/90,±45, 0/90] which have the lowest tensile strength. It can be observed that the highest strength improvement factor was 89% for laminate $[0/90]_3$.

$$SIF=\frac{UTS-UTSref}{UTSref}\times 100 \qquad \text{...(3-2)}$$

Where UTS is the ultimate tensile stress and UTS_{ref} is the ultimate tensile stress of [90/0, ±45, 0/90] laminate (the lowest ultimate tensile strength).

Table 3-9,
The Percentage Strength Improvement Factor (SIF %) for Laminates

laminate Description	SIF %
$[CSM]_3$	9.366
$[0/90]_3$	89.037
[0/90, CSM, 0/90]	81.13
[CSM, 0/90, CSM]	14.379
[0/90,±45, 0/90]	0

3.3.2. Fatigue Life Improvement Factor (FLIF)

Table (3-10) shows empirical life (number of cycles to failure) for each laminate at different applied stresses amplitude. The lowest life was for [0/90, ±45, 0/90] laminate and slightly higher for [0/90, CSM, 0/90] laminate. Table (3-11) shows the percentage of fatigue life improvement factor (FLIF %) at each applied stresses

$$FLIF=\frac{Log\ Nf-Log\ Nf\ ref.}{Log\ Nf\ ref.}\times 100 \qquad \text{...(3-3)}$$

Where the N_f is the number of cycles to failure and N_{fref} is the number of cycles of laminate [0/90, ±45, 0/90] (the lowest life at each level of applied stress as a reference).It can be observed the (FLIF) increased with decreasing of applied stresses, and it can perform the relationship between the applied stress amplitude and the (FLIF) as the equation of power law regression is given by[14]:

$$\sigma = c(FLIF\%)^d \qquad \text{...(3-4)}$$

Where (. is the applied stress amplitude, and (***c***), (***d***) are the fitting parameters which are dependent upon the type of the fiber glass mat. The regression constants representative of the (FLIF) trends, from the model, are given in Table (3-12).Figure (3-2) show these relations.

Table 3-10,
Empirical Number of Cycles To Failure (N_f) for Laminates at Different Level of Applied Stresses Amplitude.

Description of laminates	Applied stresses amplitude			
	140MPa	120MPa	100MPa	80MPa
$[CSM]_3$	29280	140349	895826	8659287
$[0/90]_3$	36067	303992	3783184	82783097
[0/90,±45,0/90]	7045	13658	32257	80645
[0/90, CSM,0/90]	9350	21740	59149	200705
[CSM, 0/90,CSM]	9873	38262	189917	1349419

Table 3-11,
The Percentage of Fatigue Life Improvement Factor (FLIF %) a Different Applied Stresses Amplitude.

Description of laminates	140Mpa	120Mpa	100Mpa	80Mpa
$[CSM]_3$	16	24.46	32	41.39
$[0/90]_3$	18.43	32.58	45.89	61.37
[0/90, CSM,0/90]	3.01	4.88	5.84	8.07
[CSM, 0/90,CSM]	3.8	10.81	17.07	24.93
[0/90, ±45, 0/90]	0	0	0	0

Table 3-12,
Fatigue Life Improvement Parameters.

laminate description	c	d
$[CSM]_3$	728.507	- 0.58119
$[0/90]_3$	545.942	- 0.4528
[0/90, CSM, 0/90]	273.02	- 0.5691
[CSM, 0/90, CSM]	213.546	-0.2803

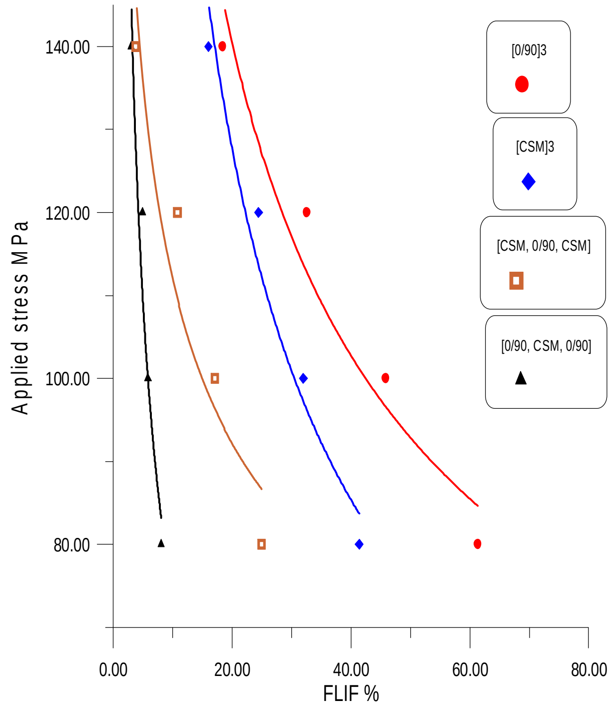

Fig. 3-2. Fatigue Life Improvement Factor % at Different Applied Stresses.

4. Conclusions

At similar volume of fraction the laminates showed:

1. Difference in strength with the difference construction of laminate (type of laminates). The maximum tensile strength for $[0/90]_3$ and [0/90, CSM, 0/90] laminates are higher than strength for $[CSM]_3$,[0/90, ±45, 0/90] and [CSM, 0/90, CSM] laminates (see Table 3-2).
2. The fatigue test results for laminates at similar volume of fraction, showed different in fatigue strength with the different construction of laminate (type of laminates). The higher fatigue strength for these laminates was found (94MPa) at 107cycles for [0/90]3 laminate (see Table 3-8).
3. The higher percentage of the strength improvement factor (SIF %) was 89% for [0/90]3 laminate (see Table 3- 9).
4. The fatigue life improvement factor (FLIF) for all laminates was increased with the decreased of applied stresses, the highest (FLIF %) was 18.43%, 32.58%, 45.89%and 61.37% for [0/90]3 laminate at 140MPa, 120MPa, 100MPa and 80MPa respectively as compared with other laminates used (see Table 3-11 and Figure 3-2)
5. The higher percentage of fatigue strength of laminates to their strength was (0.545) for [CSM]3 laminate and the lower percentage of fatigue strength to their strength was (0.15) for laminate [0/90, CSM, 0/90].
6. The maximum strength laminate was the best fatigue behavior at constant amplitude stress which was for laminate [0/90]3 (see Figure 3-1)

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تأثير نوع حصيرة الا لياف الزجاجية على سلوك الكلال للمواد المتراكبة عند نسبة حجميه ثابتة للالياف الزجاجية

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الخلاصة

يهدف البحث الحالي الى دراسة تأثير نوع طبقات اللالياف الزجاجية على سلوك الكلال للمواد المتراكبه المصنعه من البولستر وبنسبه حجميه ثابتة للألياف الزجاجية مقدارها ٣٣%. أظهرت نتائج البحث ان المواد المصنعه من [0/90 ,45±,0/90] ,[0/90, CSM, 0/90] تمتلك أدنى حد للكلال عند ١٠٧ من تلك للمواد المصنعه من 3[0/90] و[CSM, 0/90, CSM], 3[CSM] على الرغم من انها تمتلك اجهاد شد اقصى مختلف وان أفضل الطبقات هي3[0/90].