Static Tensile Strength And Fatigue Behavior Of Polyester Reinforced With The Chopped Strand Mat (CSM) Offiber Glassat Elevated Temperature

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Abstract:

In the work present, describes an attempt has been made to study the effect of temperature on fatigue behavior of polyester reinforced with woven of fiber glass manufactured as a laminate [CSM]$_3$.Fatigue tests were carried out at constant stress amplitude at different temperature environment. All fatigue tests were employed at stress ratio R=-1 and under constant fiber volume fraction (VF) of 33%. The results indicated that the tensile and the fatigue strength decreased with increasing temperature up to at 60 ^{0}C.The fatigue life reduction factor (FLRF) at 60 ^{o}C was in range (41%-61%) in range of applied stresses amplitude between (80-100MPa) compared at (RT).

Keywords: ***tensile strength, Fatigue, polyester, Fiber glass mat, elevated temperature***

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مقاومة الشد وسلوك الكلال لمادة البولسنر المدعم بطبقات اللالياف الزجاجية نوع(حصيرة الخيوط القصيرة)عند درجات حرارة مختلفة

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الخلاصة:

الهدف من هذا العمل هو دراسة تأثير درجة الحرارة على مقاومة الشد وسلوك الكلال لمادة البولستر المدعم بطبقات الالياف الزجاجية نوع (حصيرة الخيوط القصيرة) وبنسبة حجمية قدرها 33 %. اظهرت النتائج ان مقاومة الشد

ومقاومة الكلال تقل مع زيادة درجةالحرارة الى 60 درجة مئوية . وان معامل تخفيض عمر الكلال عند 60 درجة مئوية كان بحدود (41 %-61 %) ضمن تأثير سعة اجهادات مسلطة ما بين (80 -100 ميكا باسكال) مقارنة عند درجة حرارة المختبر

1. Introduction

Composite materials are discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and is called the reinforcement material; whereas the continuous phase is usually softer and is termed the matrix.The matrix holds the reinforcements in an orderly pattern [1, 2]. Fibre-reinforced composites have been considered as a replacement of metals and alloys in a number of engineering structures due to their favorable characteristics including superior specific strength and stiffness (strength-to-weight ratio and stiffness-toweight ratio, respectively. As fibre reinforced plastics are inhomogeneous and anisotropic, the mechanism of fatigue in fibre-reinforced composite materials is considerably different from that of conventional materials. The fluctuating loads may accumulate a substantialnumber of micro-damages in matrix, which cause the final failure of composites in a general fashion as opposed to the final failure by the propagation of a single crack in metals. There are many different types of most common fatigue prediction approaches for fibrous composites. One of all, a widespread fatigue life model is characterized by a fatigue failure criterion based on the fatiguedamage information from conventional S–N curves. [3]

Owen, et.al[4]: performed many tests on chopped strand mat impregnated with polyester resin. Upon static and fatigue testing, damage was apparent at only thirty percent of the ultimate strength of the material. This damage was associated with fibers perpendicular to the loading direction, and was initiated at many points on the strands. At a load of twenty percent of the ultimate strength, damage was found along the interface between fibers and matrix at only one thousand cycles. The laminate could be expected to survive at least one million cycles before breaking into two pieces even thought damage had begun two orders of magnitude of cycles earlier.

C.M.Branco, et.al [5]: investigated the phenol matrix reinforced by unidirectional E-glass with volume fraction 0.3 and 0.45. The composite specimens are tested at ambient condition and temperature of 100, 150, 200 ^{o}C with stress levels of R equal to 0, 0.4 for load frequencies of 1.5, 10, 25 Hz.Fatigue strength decreased with increasing temperature from 20 to 200 ^{o}C for both volume fraction of 0.3 and 0.45. This effect was more pronounced in the lower cycle’s regime.

J.A.M. Ferreira, et.al [6]:studied fatigue of polypropylene/glass thermoplastic composites produced from a bidirectional woven cloth mixture of E glass and polypropylene. The latter becomes the matrix after the application of heat and pressure. This composite was manufactured with a volume fraction Vf of 0.338. The effect of layer design on the static and fatigue performance was investigated. The results showed; the fatigue strength was influenced by the layer design and the loss of stiffness (E/E_o) started early in the fatigue life, also it can observed a linear relationship between the loss of stiffness and the temperature rise.

A.Bernasconi et al [7]: studied the effect of the temperature and frequency on fatigue behavior of short glass fiber reinforced (30% weight) polyaminde-6. Tensile strength and fatigue(tension-tension with stress ratio=0.1) tests were performed at 23 and 50^{o}C. The results show of an increment in temperature during tensile tests is decrease of ultimate tensile strength and elastic modulus from 109, 5800MPa to 84, 4300MPa respectively also the fatigue strength at 10^6 cycles decreased from 52.5 to 47.5MPa.

Al-alkawi, et.al [8]: 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 higher percentage reduction in strength was 23% at 60^{o}C as compared to (RT) for $[CSM]_3$ laminate.

2. Experimental Work

Materials:

In this work, E-Glass fiber is used which it was obtained in the form of discontinuous and continuous woven strand mats. 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% hardenerwas 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 fibres: [9]

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 fibre glass and polyester (Resin) [9]

Material	Density g/cm3	Modulus of elastic (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

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 [10] more details can be found clear in reference [8].

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

The Tensile Test Specimens:

Matrix: In order to find the mechanical properties of the matrix, tensile specimens were prepared according to ASTM D 638-97 [11]. Figure 2-1 shows the dimensions and geometry of tensile specimen for the matrix.

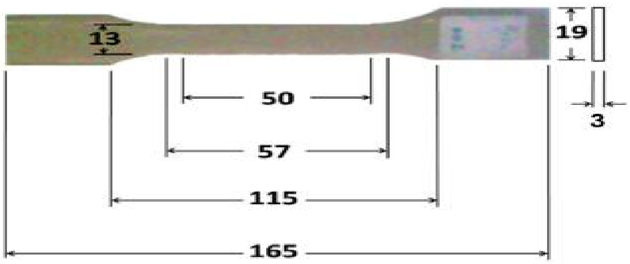


Fig.(2-1) the polyesterspecimen [11] (Dimensions are in mm)

Composite Material:

Tests specimens were designed according to ASTM D3039 standards [12]. The tensile test specimen configuration is shown in **Figure (2-2).**

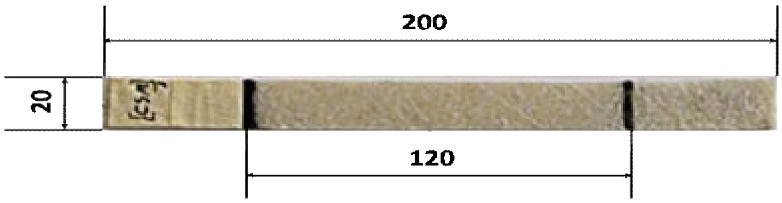


Fig. (2-2)tensile test specimen dimensions(Dimensions are in mm)

Tensile Tests Procedure

The tensile tests were performed in a Tinius Olsen (H50KT) test machine at room, 40^{o}C,50^{o}C and60^{o}C 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 with the furnace mounted in place. Tests are carried out at a constant speed of 1 mm/min[3].

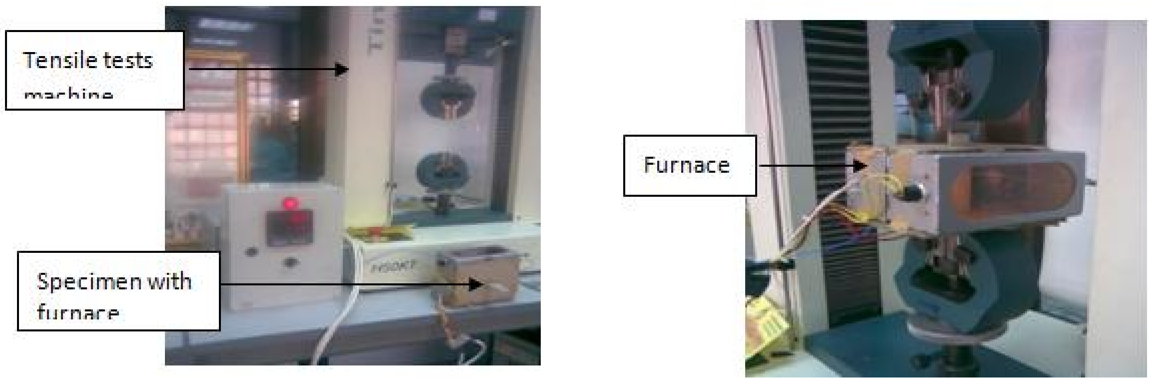


Fig. (2-3) a-Specimen with the Furnace b- Specimen Fixture with the Furnace

The test results show a brittle fracture of the matrix and gradual breaking of the fibers.

Temperature Control Circuit:

The circuit shown in **Figure (2-4)** represents the operation of the temperature control board. The temperature control circuit is used to control the temperature inside the furnace by its thermostat, which switches off the electrical power when the temperature reaches the required temperature and switches it on when the temperature drops below the required temperature. The temperature inside the furnace is calibrated by using a digital thermometer with a thermocouple. The results are accurate within ± 0.2^{o}Cand the heating rate is 1^{0}C/min. [8]

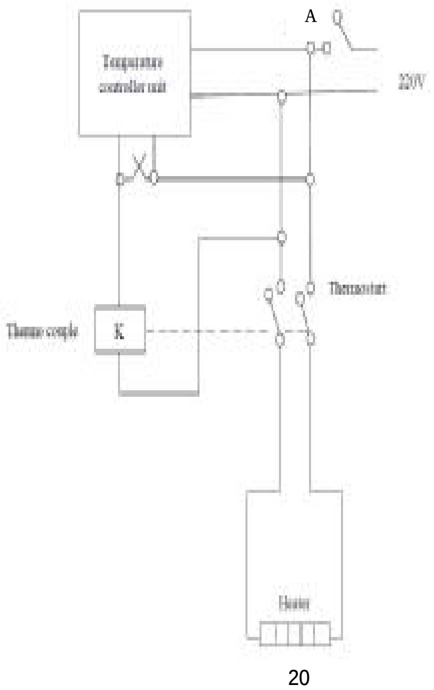


Fig. (2-4) Diagram of the temperature control circuit

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 [3].

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 [13].

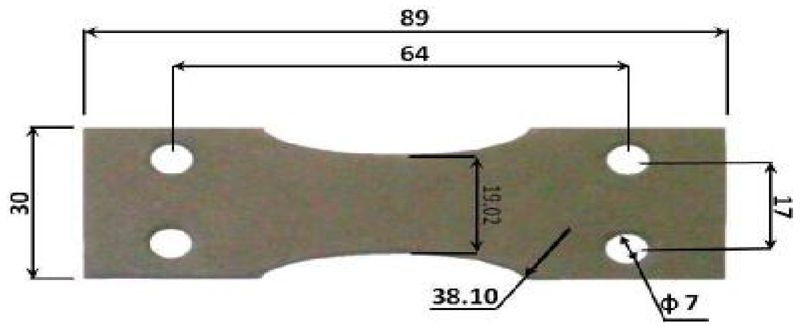
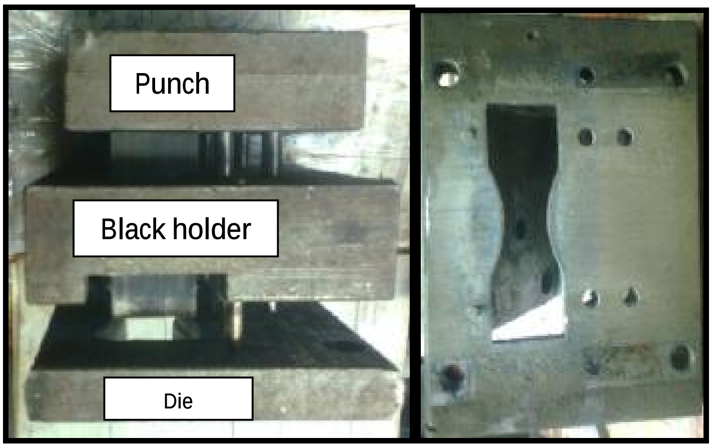


Fig. (2-5) Fatigue Specimens (all dimension in *mm*) [14]

In order to obtain a good cutting for specimen, a cutting die was designed as shown in **Figure (2-6)** was made from steel and stainless steel which is resistant to corrosion and the load range over the specimens whosecutter.

It isconsisting of three parts, the first stage can be cutting 4-holes, and the second stage can be cutting the specimen.



Cutting die assembly front view for die

Fig. (2-6) cutting die for fatigue specimen

Fatigue Tests Procedure

A 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 at room temperature, 40, 50 and 60°C. The AVERY Fatigue Testing Machine Type-7305 was designed to apply reverse loads with or without an initial static load as shown in Figure (2-7). 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 applied moment and the deflection angle (Appendix-A) A revolution counter is fitted to the motor to record the number of cycles. The cycling rate is 1400 rpm. [13]

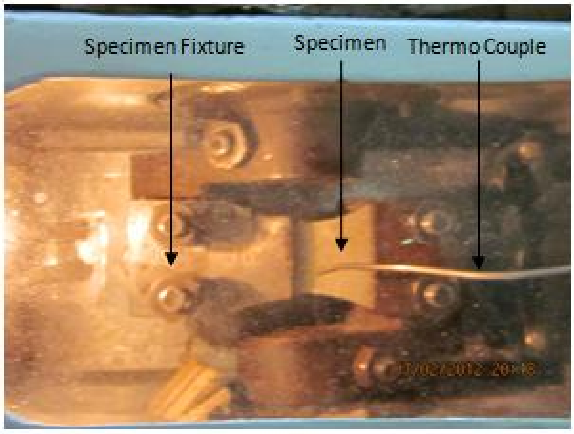


Figure (2-7)

a) AVERY Fatigue Testing Machine Type 7305 b) Close up of Specimen Fixturein furnace

The cyclicreveres bending stresses means tension-compression stresses, so the machine was adjusted at stress ratio **R= -1**.

3. Experimental results and discussion

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)

Matrix , Resin	specimens			Ultimate tensile stress UTS, MPa			Average UTS MPa
Polyester.TOPAZ 1110	1	2		33.38	31.75	32.59	32.567

Table (3-2) tensile strength for $[CSM]_3$ laminate at differenttemperatures

Temperature °C	specimens			Ultimate tensile stress (UTS) (MPa)			Average UTS(MPa)
30 (RT)	4	5	6	142	142.5	147.5	144
40	7	8	9	134.7	130.5	128	131
50	10	11	12	117.2	112	115	115
60	13	14	15	110.9	109.2	110.1	110

Table (3-3) coefficient C, constant material for laminate [CSM]$_3$ with V_f=33%

No.	laminate description	C_0	C_1	C_2	C_3	correlation coefficient R^2
1	[CSM]$_3$	25	10.716	-0.295	0.00233	1

According to the obtained results it can be observed the ultimate tensile strength for this laminate as a polynomial expression of third order can fit the experimental data to include the temperature effect as a function of the temperature (T):[8]

$$\sigma_{ult} = C_0 + C_1 T + C_2 T^2 + C_3 T^3 \quad \ldots\ldots (3\text{-}1)$$

Where σ_{ult} is the ultimate tensile strength (MPa), T is the temperature in ^{o}C and the coefficient C with subscripts 0, 1, 2, 3 represent material constant which can be obtained from experiments as shown in **Table (3-3)**and in **Figure (3-1).**

Strength reductionfactor (SIF):

Table (3-4) shows strength reduction factor (SRF) for laminates [CSM]$_3$, based on the test at (RT) which have the higher tensile strength comparing with that at other temperature test. It can be observed that the lowest strength reduction factor was 23.6% for laminate at 60 ^{0}C.

$$\text{SRF\%} = \frac{UTS_T - UTS_{RT}}{UTS_{RT}} \times 100 \quad \ldots\ldots (3\text{-}2)$$

Where UTS_{RT} is the ultimate tensile stress at (RT) and UTS_T is the ultimate tensile stress at certain temperature for [CSM] $_3$laminate.

Table (3-4)the percentage strength reduction factor (SRF %) for [CSM}$_3$laminates at different temperature

Temperature ^{o}C	RT	40	50	60
SRF %	---	9.02	20.1	23.6

Fatigue test results:

Tables (3-5)to(3-8) show fatigue test results at a constant amplitude load for laminates $[CSM]_3$ at room temperature (RT), 40 ,50 and 60^0 C respectively. The S-N curve was obtained from these results as shown in figure (3-2).The equation of power law regression is given by [14]:

$$\sigma_f = aN_f^{\,b} \qquad \text{..... (3-3)}$$

Where (σ_f is the applied stress amplitude at failure, (N_f) is the number of cycles to failure and (***a***),(***b***) are the fitting parameters. The regression constants representative of the fatigue trends, from the model, and the fatigue strength at 10^6 cycles are given in Table (3-9). The higher fatigue strength at 10^6 cycles was 78.536MPa at (RT)and the lower fatigue strength was 54.543MPa at temperature ($60\ ^0$ C), then it can be observed that the fatigue strength of this laminate was decreases with the increasing temperature as a polynomial question of third order can fit the experimental data to include the temperature effect as a function of the temperature (T): [15]

$$\sigma_e = D_o + D_1T + D_2T^2 + D_3T^3 \text{........ (3-4)}$$

Where $\sigma_e$is the fatigue strength (MPa) at 10^6 cycles, T is the temperature in ^{o}C and the coefficient D with subscripts 0, 1, 2 and 3 represent material constant which can be obtained from experiments as shown in table (3-10),then from equation (3-3) and(3-4) it can be say:

$$N = \left(\frac{D_0 + D_1T + D_2T^2 + D_3T^3}{a}\right)^{\frac{1}{b}} \text{.........(3-5)}$$

Table (3-5) fatigue results for laminate $[CSM]_3$at (RT)

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave}$.
16, 17, 18	108.39	60000, 50000,55000	55000
19, 20, 21	91.71	360000, 406000, 380000	382000
22, 23, 24	81.18	900000, 989000, 850000	913000
25, 26, 27	73.717	1150000, 1220000, 1380000	1250000

Table (3-6) fatigue results for laminate $[CSM]_3$ at 40 ^0C

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
28, 29, 30	98.197	29500, 26500, 24500	26833
31, 32, 33	86.688	82000, 65000, 80000	75666
34,35, 36	75.957	630000, 546000, 720000	632000
37, 38, 39	68.122	1085000, 1140000, 1225000	1150000

Table (3-7) fatigue results for laminate $[CSM]_3$ at 50 ^0C

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
40, 41, 42	90.256	7000, 5000, 6000	6000
43, 44, 45	78.214	58500, 45000,55000	53000
46, 47, 48	68.025	450000, 510000, 426000	462000
49, 50, 51	60.198	990000, 1040000, 1185000	1071000

Table (3-8) fatigue results for laminate $[CSM]_3$ at 60 ^0C

Specimens No.	Applied stress amplitude(MPa)	Number of cycles to failure (N_F)	$(N_f)_{ave.}$
52, 53, 54	81.836	3900, 4400, 4500	4250
55, 56, 57	75.047	6200, 7300, 6000	6500
58, 59, 60	67.798	20000, 17500, 18000	18500
61, 62, 63	60.924	232500, 245000, 270000	249000
64	49.804	1500000	No failure

Table (3-9) Fatigue parameters and fatigue strength for laminate $[CSM]_3$ at different temperature

Temperature °C	a	b	Fatigue strength at 10^6 cycles (MPa)	Reduction in Fatigue strength at 10^6 cycles(MPa)	correlation coefficient R^2
RT	395.094	-0.11692	78.536	-	0.94
40	242.79	-0.08951	70.495	10.238%	0.953
50	170.864	-0.07298	62.337	20.626%	0.974
60	134.508	-0.06523	54.343	30.805%	0.93

Table (3-10) coefficient D, constant material for laminate $[CSM]_3$ with V_f=33%

No.	laminate description	D_0	D_1	D_2	D_3	correlation coefficient R^2
1	$[CSM]_3$	99.147	-0.54303	-0.00620	4.683×10^{-5}	1

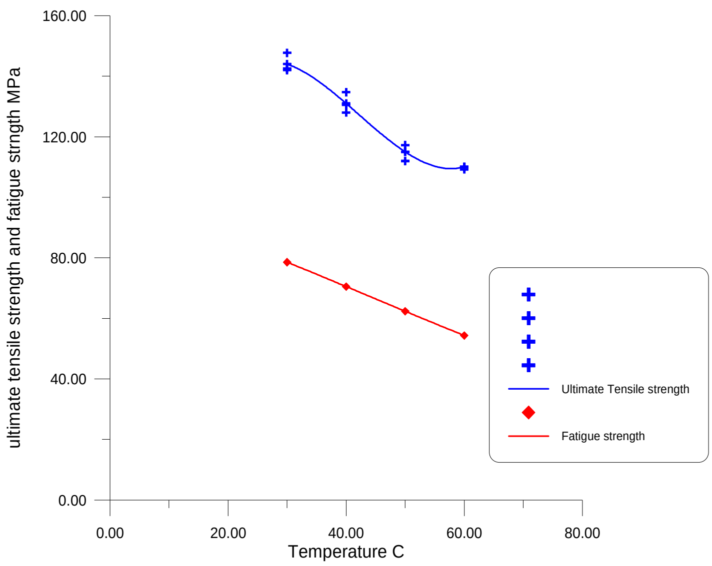


Fig. (3-1) fatigue strength and ultimate tensile strength at different temperature for laminate

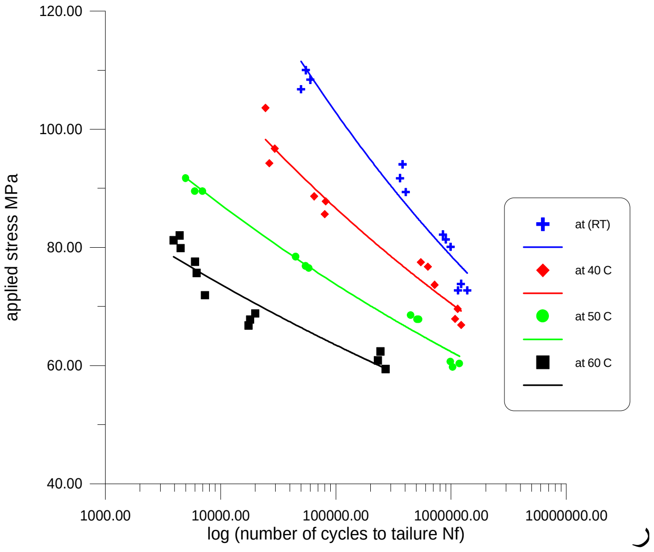


Fig. (3-2) S-N curve for $[CSM]_3$ laminate at different temperature

Fatigue life Reduction factor:

Table (3-11) shows empirical life (number of cycles to failure) for $[CSM]_3$ laminate at different applied stresses and at different temperature The lowest life was at 60 ^oC. **Table (3-12)** shows the percentage of fatigue life reduction factor (FLRF %) at each applied stresses[16] :

FLRF%= ×**100**. . . . (3-4)

Where the $N_{f(RT)}$ is the number of cycles to failure at RT and $N_{f(T)}$ is the number of cycles to failure at certain temperature for laminate $[CSM]_3$. It can be observed the (FLRF) decreased with increasing of temperature. Then it can be observed the fatigue life reduction decreased with decreased applied stress even it tested at 40, 50, 60 ^oC as shown in **Table 3-12.**

Table (3-11) empirical number of cycles to failure ($N_{f(RT)}$) and ($N_{f(T)}$) for laminates at different level of applied stresses amplitude

Temperature ^oC	Applied stresses amplitude		
	100MPa	90MPa	80MPa
RT	126909	312500	855757
40	20123	65298	243426
50	1540	6525	32773
60	94	473	2881

Table (3-12) the percentage of fatigue Life reduction factor (FLRF %) at different applied stresses amplitude and different temperature based to RT

Temperature °C	100MPa	90MPa	80MPa
RT	-	-	-
40	15.67	12.37	9.20
50	37.54	30.57	23.88
60	61.33	51.32	41.68

The observed effect of on the results of the strength reduction factor (SRF) and the fatigue strength reduction factor (FSRF) is similar to the finding of Ref. [7, and 17] as shown in **Table (3-13).**

Table (3-13) comparison between the present results with previous ones

No.	Item	Reference 7 Short-glassfiber reinforced polyamide-6 (W_f=30%)	Reference 17 UD E-glass Reinforced epoxy	Current work Chopped strand mat E-glass Reinforced polyester (V_f=33%)
1	Tensile strength	At 23°C=109MPa At 50°C=84MPa Strength reduction =22.9%	At 23°C=915MPa At60°C=737MPa Strength reduction =19.45%	At 30°C=144MPa At 50°C=115MPa Strength reduction =20.1%
2	Elastic modulus	At 23°C=5800MPa At 50°C=4300MPa reduction =25.8%	At 23°C=38.2GPa At60°C=35.1GPa reduction =8.1%	At 30°C=4350MPa At 60°C=3500MPa reduction =19.54%
3	Fatigue strength at 10^6 cycles	At 23°C=52.5MPa At 50°C=47.5MPa Reduction =9.52% R=0.1	At 23°C=220MPa At60°C=170MPa Reduction=22.27% R=-1	At 30°C=78.536MPa At 60°C=54.543MPa Reduction =30.8% R=-1
4	Fatigue lifereduction At 60°C	---	30% at loading stress 200MPa	41% at loading stress 80MPa 61% at loading stress 100MPa

Discussion:

In general, most inorganic fibers are not very sensitive to the range of temperature applicable to polymer composites; the matrix is sensitive to thermal conditions. A thermo set polymer (polyester) system is in a glassy (stiff and brittle) state if its temperature is below a threshold usually known as the glass transition temperature (T_g) (glass transition temperature for polyester is 69°C [2]). If the temperature approaches this threshold, the polymers stiffness rapidly declines and internal damping increase until the material reaches a state where viscous effects are dominate. This condition is known as the rubbery state. At elevated temperatures, dilatation allow for increased chain mobility, resulting in a loss of modulus and increase in internal damping[17].That is the main reason to observed the higher reduction in tensile strength, fatigue strength and fatigue life was at 60°C for composite used in this work.

Optical microscopy analysis:

Examples of some specimens after fatigue testfailure is shown in **Figure (3-3)** and **Figure (3-4)** show the micrographs of fatigue failure.

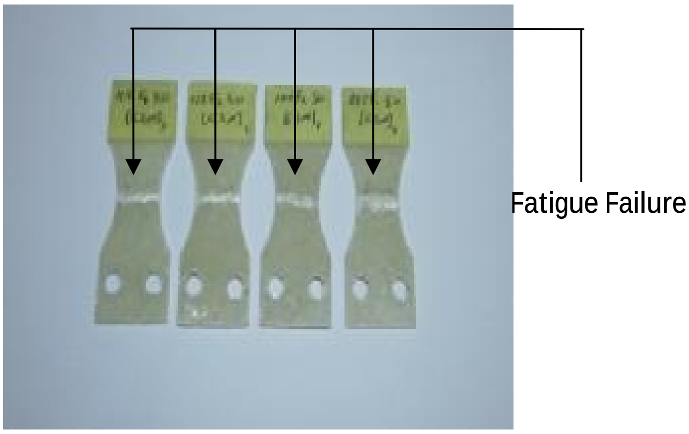


Figure (3-3) Fatigue Failureof Composite Specimens

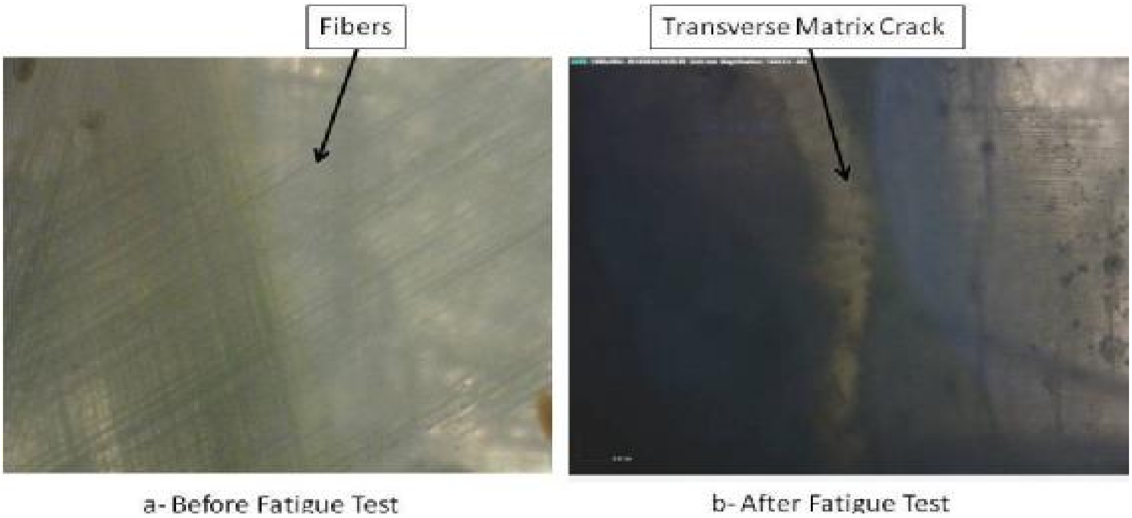


Figure (3-4) micrographs of fatigue failure observed in polyester-E glass composite (40X)

From above figures the fatigue damage in the composite initiates by the formation of transverse matrix cracks, which 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.

Optical microscopic examinations of some specimens subjected to fatigue test indicated the damage may have started very early in the matrix followed by fiber-matrix debonding and pull out of fibers from the matrix.

4. Conclusions:

1- For polyester reinforced with woven E-glass $[CSM]_3$laminate at a fiber volume fraction of 33%The tensile strength decreases with increasing temperature up to 60 ^oC .
2- The percentage reduction factor for tensile strength (SRF %) and for fatigue strength (FSRF %) at 10^6 cycles at 60^oC was 23.6% and 30.805% respectively compared to that at (RT).
3- The fatigue life reduction factor (FLRF)reduced when the applied stresses decreased at all tested temperatures.
4- The fatigue life reduction factor (FLRF) at 60 ^oC was in range (41%-61%) in range of applied stresses amplitude between (80-100MPa).

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Appendix-A

In order to provide a known bending stress in a cantilever several variable have to be considered simultaneously. The simple theory of a cantilever is as follows [18]:-

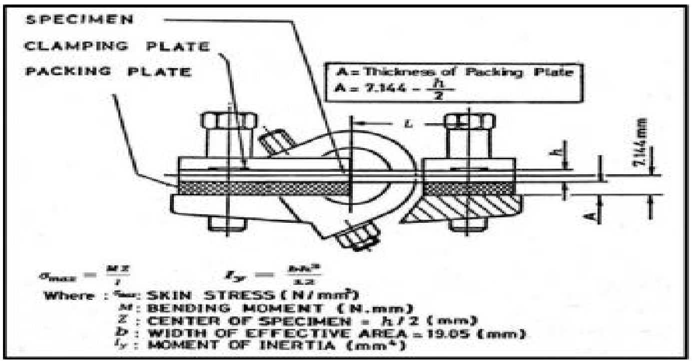

Fig. (A-1)Schematic Representation of Fixing Method, And how to Calculate Bending stress [13]

Max. Bending moment $M = WL$

Max. Bending stress $\sigma = \frac{M.z}{I}$

Where the strip cantilever is (b) width, (h) thick and (L) length, (E) elastic modulus, (W) Load on free end

Free end deflection $\delta = \frac{WL^3}{3EI}$

$\delta = \frac{ML^2}{3EI}$ … (A-1)

Where, $z = \frac{h}{2}$, then δ= ….. (A-2)

A further correction is necessary to take into account the curvature of the cantilever when determining the maximum bending moment. Then reduction in length is given by [19]:

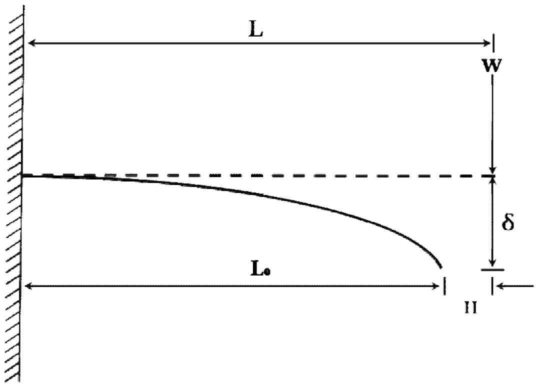

Fig. (A-2) Schematic Representation of curvature of the cantilever

H=

……. (A-3)

And assuming the curvature can be approximated by:

$Y = \delta\,(1-\cos\frac{\pi x}{2L})$

Then $= \frac{\delta\pi}{2L}\sin\frac{\pi x}{2L}$

By substituting ($(dy)/d$) in equation (A-3) and integrating it, then:

$H = \frac{\delta^2\pi^2}{16L} = \frac{0.616225\delta^2}{L}$ … (A-4)

The maximum bending moment is thus;

$M = W(L - H) = WL_o$ ...... (A-5)

Then, $L = \frac{1}{2}L_o + \sqrt{0.25L_o^2 + 0.61625\delta^2}$

This enables (L_o) to be calculated;

$(2L - L_o)^2 = L_o^2 + 2.465\delta^2$

$4L^2 - 4LL_o + L_o^2 = L_o^2 + 2.465\delta^2$

$L_o = \frac{4L^2 - 2.465\delta^2}{4L}$

If L =32.94mm, and from calibration curve figure (A-3) for δ, then;

$L_o = \frac{4340.1744 - 2.465\delta^2}{131.76}$ ... (A-6)

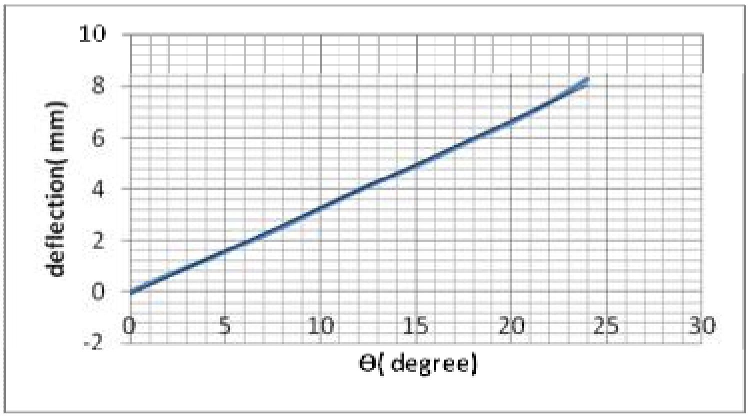

Fig. (A-3)) calibration curve between bending deflection and eccentric position angle (Θ)

For different position of eccentric point the effective length (L_o) was;

Theta (degree)	δ_{max}(mm)	L_o (mm)
24^o	8.25	31.6667
22^0	7.35	31.9293
20^o	6.60	32.1251
18^o	5.90	32.2887
16^o	5.25	32.4243
14^o	4.60	32.5441

Then the maximum bending stress can be calculated from equation (A-7);

$\sigma = \frac{1.5Eh\delta}{L_o^2}$ ... (A-7)