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Fatigue behavior of woven glass fiber reinforced polyester under variable temperature

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ABSTRACT

In the work present, describes an attempt has been made to study the effect of temperature on plain fatigue behavior of polyester reinforced with woven of fiber glass manufactured as a laminate $[0/90]_3$.Fatigue tests were carried out at constant and variable 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 strength reduction factor (FLRF) at 60 ^{o}C was (46%) compared to (RT) environment. A nonlinear fatigue damage model was proposed taking into account the effect of temperature sequence and fatigue loading. This model was calibrated against experimental data under different thermal conditions. The final conclusion which derived from this work was the verification of the model results with the experimental ones.

Introduction

Composite material is 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 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. One of the foremost demands in design criteria and maintenance strategies is to develop a reliable and convenient fatigue damage model estimating the remaining life of materials. As fibre reinforced plastics are inhomogeneous and anisotropic, the mechanism of fatigue is considerably different from that of conventional materials. The fluctuating loads may accumulate a substantial number 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 common fatigue prediction approaches for fibrous composites. One of the widespread fatigue life models is characterized by a fatigue failure criterion based on the fatigue damage information from conventional S–N curves. [3]

Z. Khan, et al [4] studied the tension-tension fatigue damage in woven carbon fabric /epoxy laminates layers at –20^{o}C, 0 ^{o}C, 24 ^{p}C 100 ^{o}C and 150 ^{o}C. Two different stacking sequences were studied; a unidirectional $[0]_8$, and an angle plied $[0, 0, 45,-45]_s$ sequence. Temperature was found to have a significant effect on the fiber/matrix bonding and inter-ply delamination characteristics of these woven carbon fabric/epoxy laminates.

C.M.Branco, et.al [5] investigated the fatigue behavior of unidirectional E-glass fiber reinforced phenol composites with volume fraction 0.3 and 0.45. The composite specimens were tested at ambient condition and temperature of 100, 150, 200 ^{o}C with stress ratios of 0, 0.4 and at 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 low cycle 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/Eo) started early in the fatigue life, also it can observed a linear relationship between the loss of stiffness and the temperature rise. C.cc

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 tests (tension-tension with stress ratio=0.1) were performed at 23 and 50^{o}C. The results showed that the increase in temperature led to a decrease in ultimate tensile strength from 109 to 84, a decrease in elastic modulus from 5800MPa to 4300MPa and the fatigue strength at 10^6 cycles 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

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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.

Experimental Work

Materials: E-Glass fiber was obtained in the form of discontinuous and continuous woven strand mats. Polyester (TOPAZ-1110 TP) unsaturated resin with1.5% hardener was used for the matrix. Table (2-1) shows the composition of E-glass fibers and Table (2-2) shows some of the reported properties of E-glass fibers and Polyester found in the literature.

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 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.

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.

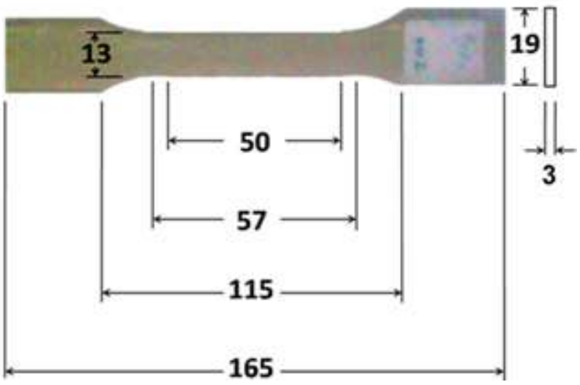

Figure 2-1: The polyester tensile test specimen [11] (Dimensions are in mm)

Composite Material:

Tests specimens were designed according to ASTM D3039 standards [12]. The tensile test specimen configuration is shown in Figure (2-3).

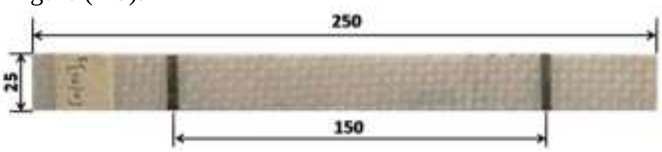

Figure 2-3: The composite tensile test specimen dimensions (Dimensions are in mm)

Tensile Tests Procedure

The tensile tests were performed in a Tinius Olsen (H50KT) test machine at room, 40^{o}C, 50^{o}C and 60^{o}C temperature. The maximum load capacity of the test machine is 5 ton. Tests were carried out at a constant speed of 1 mm/min [3].The test results show a brittle fracture of the matrix and gradual breaking of the fibers. Figure (2-4) shows some examples of tensile test specimens after failure.

Figure (2-4) Examples of tensile specimens after failures

Temperature Control Circuit:

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}C and the heating rate is 1^{0}C/min. [8]

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 for flat plate specimens. Figure (2-5) shows the shape and dimensions of the fatigue specimen [13].

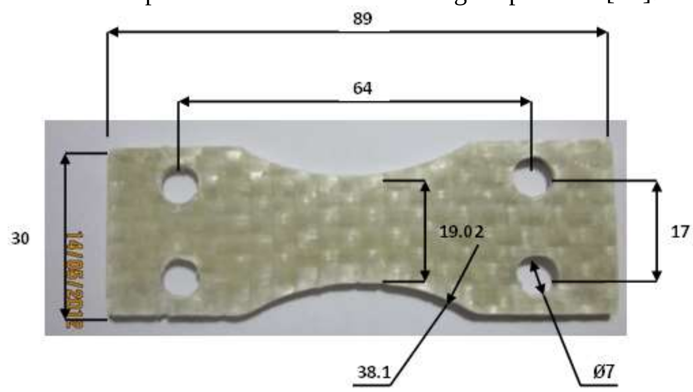

Figure (2-5) Fatigue Specimens (all dimensions in *mm*) [14]

Fatigue Tests Procedure

A cyclic bending fatigue testing procedure was used. 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^{o}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 (2-6). 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. [13]

The applied stress is calculated from the applied moment and the deflection angle. A revolution counter is fitted to the motor to record the number of cycles. The cycling frequency is 1400 rpm and the stress ratio is R=-1 in all tests.

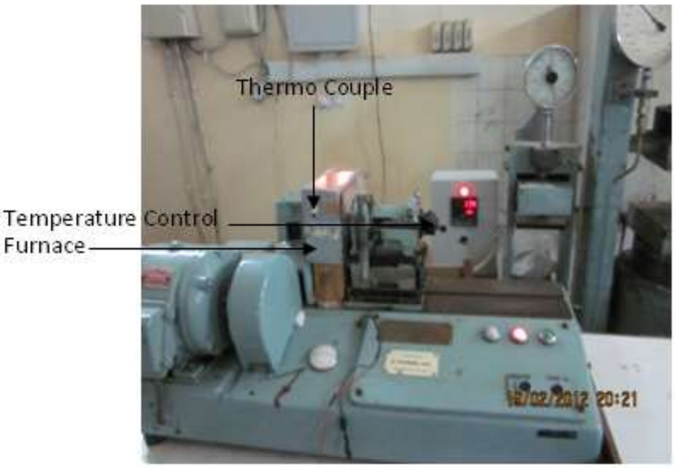

Figure (2-6) AVERY Fatigue Testing Machine Type 7305

The fatigue tests were done under constant stress amplitude at different temperatures RT, 40, 50, 60°C and at sequence temperature.

Experimental results and discussion

Tensile strength:

Table 3-1 and 3-2 shows the experimental tensile strength and the elastic modulus of the matrix at room temperature (RT) and composite at different temperatures. Elastic modulus (E) was calculated by constructing a secant between two points, typically at strain values of 0.001 and 0.003 [3].

Table (3-1) Tensile test for matrix (polyester) at (RT) [8]

Matrix , Resin	UTS (MPa)	Elastic modulus (E) (MPa)
Polyester, TOPAZ 1110	32.5	916

Table (3-2) tensile strength for $[0/90]_3$ laminate at different temperatures [8]

Temperature °C	UTS (MPa)	Elastic modulus (E) (MPa)
30 (RT)	249	6240
40	242	5500
50	239	5000
60	222	4650

The ultimate tensile strength for this laminate can be expressed as a polynomial of third order with temperature to fit the experimental data [8]:

$$\sigma_{ult} = C_o + C_1T + C_2T^2 + C_3T^3 \quad \ldots\ldots (3\text{-}1)$$

where σ_{ult} is the ultimate tensile strength in (MPa), T is the temperature in °C and the coefficient C with subscripts 0, 1, 2, 3 represent material constants which can be obtained from experiments as shown in table (3-3).

Table (3-3) coefficient C, constant material for laminate $[0/90]_3$ with V_f=33%

No.	laminate description	C_0	C_1	C_2	C_3	correlation coefficient R^2
1	$[0/90]_3$	114	10.8	-0.27	0.002	1

Strength reduction factor (SIF):

Table (3-4) shows strength reduction factor (SRF) for laminates $[0/90]_3$, based on the test at (RT). It can be observed that the lowest strength reduction factor was 10.84% for laminate at 60 °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 $[0/90]_3$ laminate.

Table (3-4) The percentage strength reduction factor (SRF %) for $[0/90]_3$ laminates at different temperature.

Temperature °C	RT	40	50	60
SRF %	---	2.81	4.01	10.84

Fatigue life:

1- Fatigue test results under Constant loading at different temperature:

The S-N curves for laminates $[0/90]_3$ at four different temperatures shown in figure (3-2). The equation of power law regression is given by [14]:

$$\sigma = aN_f^{\ b} \quad \ldots\ldots (3\text{-}3)$$

Where (σ) is the applied stress amplitude, (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 (3-5). The highest fatigue strength at 10^6 cycles was 115.56MPa at (RT) and the lowest fatigue strength was 61.54MPa at temperature (60 °C). It can be observed that the fatigue strength of this laminate decreases with increasing temperature and a polynomial of third order can fit the experimental data [15]:

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

where σ_e is the fatigue strength (MPa) at 10^6 cycles, T is the temperature in °C and the coefficients D with subscripts 0, 1, 2 and 3 represent material constant which can be obtained from experiments as shown in table (3-6).From equations (3-3) and(3-4) it can be shown that:

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

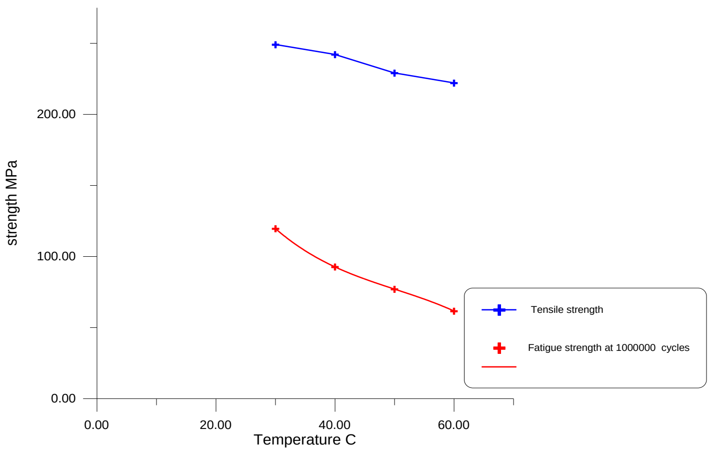

Figure (3-1) fatigue strength and ultimate tensile strength at different temperature

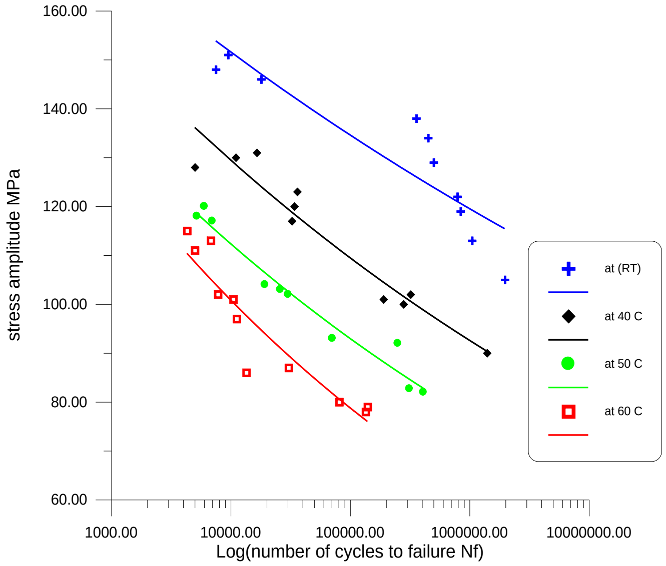

Figure (3-2) S-N curve for $[0/90]_3$ laminate at different temperature

The observed effect of temperature on the results of the strength reduction factor (SRF) and the fatigue strength reduction factor (FSRF) is similar to the finding of Ref. [4, and 17] as shown in table (3-8).

2-Fatigue life under sequence loading and sequence temperature:

Tables (3-8) to (3-11) show fatigue test results under sequence loading and sequence temperature for laminates $[0/90]_3$.

Proposed model:

The experimental fatigue damage (D_{exp}) can be written as:

$$D_{exp} = \sum_{i=1}^{m} \frac{n_{iT}}{N_{fT}} \quad \text{.... (3-6)}$$

where; n_{iT} represents the number of cycles at a certain temperature under sequence loading, N_{fT} represents the number of cycles to failure under constant loading at the same temperature, and m is the number of stress range level.

Nijssen et al. [18] they proposed a damage model for composite materials under repeated two blocks loading as shown in figure 3-2

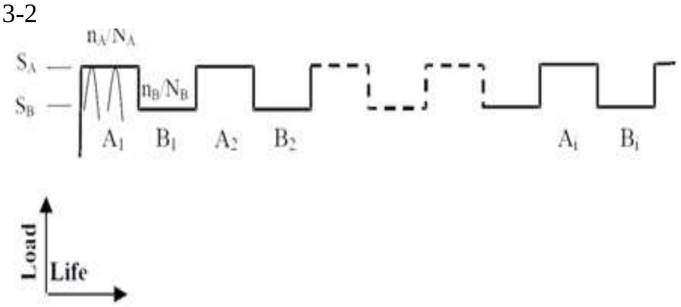

Figure 3-2: Schematic of repeated blocks tests

A few simplifications can be made by assuming, that the life fractions per block are equal, and that each block has an equal strength degradation parameter *C*:

$$C_A = C_B \,, \qquad \frac{n_A}{N_A} = \frac{n_B}{N_B}$$

$$D = 2\frac{k^{1/c}}{1+k^{1/c}} \quad \text{(When the failure occurs within block A)} \quad \text{...... (3-7)}$$

Or,

$$D = 2\frac{1}{1+k^{1/c}} \quad \text{(When the failure occurs within block B)} \quad \text{...... (3-8)}$$

where; $k = \frac{S_o - S_A}{S_o - S_B}$, S_o- Initial strength, S_A, S_B Maximum applied stresses for block A and B respectively.

Then it can propose nonlinear model for fatigue damage under sequence temperature as:

$$D_{NMFD} = \frac{1}{m}\left[\left\{\left(\frac{S_{oA}-S_A}{S_{oB}-S_B}\right)^{f_1(b,T)} + \left(\frac{S_{oB}-S_B}{S_{oC}-S_C}\right)^{f_2(b,T)} + \dots\dots\dots\right\}\right] \quad \text{...... (3-9)}$$

where; $f_1(b,T)$ and $f_2(b,T)$ represent a function of b the slope of S-N curve at a constant temperature and T the temperature in °C at sequence temperature block while these parameters decreasing the strength, it can attempt to assume these parameter as;

$$f_1(b,T) = \frac{D_A}{D_B}, \quad D_A = \frac{b_A}{T_A} \quad \text{and } D_B = \frac{b_B}{T_B}, \text{ where}$$

D_A and D_B strength degradation parameter $(D_A \neq D_B)$ then;

$$f_1(b,T) = \frac{b_A\, T_B}{b_B\, T_A}, \quad f_2(b,T) = \frac{b_B\, T_C}{b_C\, T_B}$$

and so on for more sequence block.

S_{oA}, S_{oB} and S_{oC} are the tensile strength at temperature A, B and C respectively, S_A, S_B, and S_C are the stress amplitude at temperature A, B and C respectively, b_A, b_B, and b_c are the slope of S-N curve at constant temperature A, B and C respectively, T_A, T_B and T_C are the temperature in °C at block A, B and C respectively and m are the number of sequence block in program.

Table (3-12) Fatigue damage for laminate $[0/90]_3$ under sequence temperature

No.	Sequence temperature	Experimental damage(D_{exp})	Miner damage (D_{min})	Proposed model Damage (D_{NMFD})
1	RT-50°C	0.3497	1	0.4590
2	RT-60°C	0.5151	1	0.4766
3	40-60°C	0.6640	1	0.5198
4	RT-40-50-60-50-40°C	0.4331	1	0.4861

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].

Table 2-1 Composition of E-glass fibers: [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 (3-5) Fatigue parameters and fatigue strength for laminate $[0/90]_3$ at different temperatures.

Temperature ^oC	a	b	Fatigue strength at 10^6 cycles (MPa)	Reduction in Fatigue strength at 10^6 cycles (MPa)
RT	297.182	-0.068367	115.563	-
40	252.926	-0.0727426	92.584	19.88%
50	239.413	-0.0821717	76.933	33.42%
60	270.65	-0.1072060	61.542	46.74%

Table (3-6) Coefficients D, constant material for laminate $[0/90]_3$ with V_f=33%.

No.	laminate description	D_0	D_1	D_2	D_3	correlation coefficient R^2
1	$[0/90]_3$	407.148	-18.4993	0.373	-0.002678	1

Table (3-7) Comparison between the present results and previous results [4, 17].

No.	Item	Reference 4 Woven carbon fiber reinforced epoxy (V_f=60%)	Reference 17 UD E-glass Reinforced epoxy	Current work Woven-roving E-glass Reinforced polyester (V_f=33%)
1	Tensile strength	-------	At 23°C=915MPa At60°C=737MPa Strength reduction =19.45%	At 30°C=249MPa At 60°C=222MPa Strength reduction =10.84%
2	Elastic modulus	--------	At 23°C=38.2GPa At60°C=35.1GPa reduction =8.1%	At 30°C=6240MPa At 60°C=4650MPa reduction =25.48%
3	Fatigue strength at 10^6 cycles	At 23°C=380MPa At 150°C=280MPa Reduction =31.5% R=0.1	At 23°C=220MPa At60°C=170MPa Reduction=22.27% R=-1	At 30°C=115.563MPa At 60°C=61.542MPa Reduction =46.74% R=-1

Table (3-8) Fatigue results under sequence loading and sequence temperature (RT-50°C) 20000 cycles per- each sequence level.

Specimen No.	Applied stress amplitude(MPa)	Temperature Sequence °C	N_f
1	108.861 80.637	(RT) 50	220000
2	110.579 81.911	(RT) 50	190000
3	108.861 80.637	(RT) 50	185000
4	112.871 83.608	(RT) 50	240000

Table (3-9) Fatigue results under sequence loading and sequence temperature (RT-60°C) 20000 cycles per-each sequence level.

Specimen No.	Applied stress amplitude(MPa)	Temperature Sequence °C	N_f
1	114.017 78.545	(RT) 60	110000
2	118.601 81.705	(RT) 60	176000
3	111.725 76.966	(RT) 60	145000
4	111.725 76.966	(RT) 60	150000

Table (3-10) Fatigue results under sequence loading and sequence temperature (40-60°C) 20000 cycles per- each sequence level.

Specimen No.	Applied stress amplitude(MPa)	Temperature Sequence °C	N_f
1	90.569 76.571	40 60	180000
2	91.035 76.966	40 60	220000
3	91.035 76.966	40 60	160000
4	93.370 78.940	40 60	160000

Table (3-11) Fatigue result under sequence loading and sequence temperature (RT-40-50-60^{o}C) 10000 cycles per-each sequence level.

Specimen No.	Applied stress amplitude(MPa)	Temperature Sequence ^{o}C	N_f
1	111.725 91.035 82.759 76.966	(RT) 40 50 60	140000
2	114.589 93.369 84.881 78.940	(RT) 40 50 60	190000
3	117.454 95.703 87.000 80.913	(RT) 40 50 60	150000
4	114.589 93.369 84.881 78.940	(RT) 40 50 60	140000

That is the main reason to observed the higher reduction in tensile strength and fatigue strength at 60^{o}C for composite used in this work.

4-Conclusions:

1- For polyester reinforced with woven E-glass $[0/90]_3$ laminate at a fiber volume fraction of 33%The tensile strength decreases with increasing temperature up to 60 ^{o}C .

2-The percentage reduction factor for fatigue strength (FSRF %) at 10^6 cycles was higher than the percentage reduction factor for tensile strength (SIF) at 40, 50 and 60^{o}C respectively.

3- A non-linear model for fatigue damage under sequence temperature was proposed which was a function of the tensile strength, the stress amplitude at the testing environment, slope of S-N curve at a constant temperature under constant amplitude loading, the number of b locks of repeated sequence temperature in one program and the temperature at each level was a safety compared with miner᾽s damage.

4-The obtained results for fatigue damage from proposed model was in agreement with the experimental results.

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