Applying Non-linear Damage Model for Predicating Corrosion Effect on Fatigue Life of (Carbon + Glass) Fibers / PMMA Composite

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ABSTRACT

The objective of this work is to investigate the salt water effects on fatigue degradation, and stress-life relationship. A series of reversed fatigue experiments were conducted on (carbon+ glass) / PMMA of salt water environments. Results indicate that the composite degrade during cycling. Exposure to salt water (salt water is used to simulate the sea water) provides the most significant reduction in fatigue life. The corrosion environment reduces the fatigue strength by 61% compared to dry fatigue. Based on previous damage model [16], corrosion – fatigue nonlinear damage model is presented in this paper, which contains one material constant; the inverse slope (α) of the S-N curve. Six specimens of two levels loading of composite material were used to verify the present model; the results showed that the predicted life is in good agreement with the experimental results.

Keywords: Corrosion- fatigue, PMMA composite material, proposed nonlinear damage model.

استخدام موديل الضرر اللاخطي لاستنتاج تأثير التاكل على عمر الكلال للمادة المتراكبة المتكونة من الياف الكربون والياف الزجاج مع البولي مثيل ميثكرلات

الخلاصة

الغرض من هذا العمل هو للتحقق من تأثير المحلول الملحي على عمر الكلال حيث اجريت سلسلة من تجارب الكلال للمادة المتراكبة المتكونة من الياف الكربون والياف الزجاج والياف البرلون مع البولي مثيل مثيكرلات .اظهرت النتائج ان المحلول الملحي (الماء المشابه لماء البحر) يقلل من عمر مقاومة الكلال بنسبة 61% .اعتمادا على انموذج الضرر السابق (16) في هذا البحث تم تقديم انموذج ضرر لا خطي للتاكل الكيمياوي الكلالي والذي يحتوي على ثابت واحد للمادة والذي هو مقلوب ميل منحني الاجهاد – عدد الدورات حيث اعطت نتائج تخمينات العمر توافقا جيدا مع النتائج العملية.

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INTRODUCTION

Fiber composites have been used for a variety of high-performance engineering structures. In general, all engineering composite structures are subjected to dynamic stresses. Also, fiber composites are susceptible to environmental degradation from long-term salt water exposure. Understanding the long-term effects of salt water on the fatigue behavior of these composites is important, however, little information is presently available [1].

Owen [2] 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.

Broutman and Sahu [3] studies the effect of the matrix on the fatigue strength of a composite martial. They concluded that epoxies had the best properties for high cycle low stress fatigue and phenolics had the best properties for short term high stress tests. Polyesters matrix materials started out with properties between phenolic and epoxy, but dropped off rapidly. For long life tests, polyester had slightly lower properties than phenolics, but much lower than epoxide materials.

Hashin and Rotem [4] 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 causes a drastic reduction in the fatigue strength compared with 0 degree loading with the off-axis angle of 60 degree, the fatigue strength at 10^5 cycles to failure has decreased to about $2.5 kg/mm^2$ from a value of about $80 kg/mm^2$ at 0 degree orientation.

Tang [5] developed the fatigue model based on cumulative damage for predicting the fatigue life of fiber reinforced polymeric composite. This model incorporates applied maximum stress, stress amplitude, loading frequency, residual tensile modulus, and material constant as parameters. The model is verified with experimental fatigue data on a glass fiber / vinyl ester composite. They are subjected to tension – tension stress at four levels of applied maximum tensile stress in each of two frequencies. Both the residual mechanical properties of specified loading cycles and the number of cycles at which specimen fail are measured. The results show that, for the material used in study, the loss in residual tensile strength and modulus in salt water is approximately the same as that in fresh water and the fatigue life in these aqueous environments is shorter than in air.

Khalifa et.al [6] 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 of 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.

David Dittenber[7] studied the effect of environment conditions on fatigue life, a regimen of test was performed on a glass/vinyl ester composite. The testing included bending fatigue test, with each type being performed under varying environmental conditions in the forms of elevated temperature and the presence of salt water. From the experimental data, it was observed that the presence of salt water caused as much as a 50% decrease in fatigue life but was dependent on the time of exposure and had little effect on short duration tests.

MATERIAL AND EQUIPMENTS

Matrix material

Poly Methyl Methacrylates (PMMA)

These are thermoplastic polymers of alkyl acrylates. Acrylic resins have good optical clarity, weatherability, surface hardness, chemical resistance, rigidity, impact strength, and dimensional stability, and has greater durability and strength. PMMA resin is increasingly popular for laminations in prosthetics because its high strength permits a thinner, lighter-weight lamination and its thermoplastic properties allow easier adjustments of the prosthesis by reheating the plastic and remolding it locally. PMMA resins tend to have a softer feel than polyester resins but are more difficult to use during fabrication**.** Their major disadvantages that they are hard and brittle [8]. The properties of PMMA are given in table (1).

Reinforcing materials Reinforcing materials include woven fiber as follows:

- **Hybrid (Fiber glass + carbon)**.
- **Perlon**

The properties of fibers are given in table (1).

Equipment

The following equipment were used:-

§ Gypsum mold (mold rectangular in shape with size (12*12*25) cm^3. (Manufactured).

§ Vacuum forming system including a vacuum pump and different types of stands, pipes, and tubes.

Procedure

All laminations were performed under vacuum according to the following procedures [11]:

- Preparing the gypsum block (containing steel beam).
- Covering the block with PVA(polyvinyl acetate)
- The fiber stockinet put on a gypsum as mentioned in figure (1-a) and the outer (PVA) was also put and keeping the smaller end positioned over the valve area by using a cotton string to tie off the (PVA) bag, and the pressure valves are opened until the pressure is approximately 30 mmHg at room temperature
- The lamination resin was then mixed with the hardening powder according to the standard ratio (2-3%), then the resulting matrix mixture was put inside

the outside (PVA) bag, and the matrix was distributed homogenously over all area of lamination stockinet, as shown in figure (1-b).

- A constant vacuum was maintained until the composite materials become cold and then the resulting lamination is lifted.

Experimental work

The tensile tests were carried out in the specialized institute for engineering industries using Tinius Olsen (H50KT) test machine with capacity of 5 ton as shown in figure (2-a). Figure (2-b) shows the specimen clamped securely in the fixture before applying the load. The load was applied at a constant rate of **1 mm/min** [12], until failure of specimen occurred and the average of three specimens was taken to evaluate the tensile behavior of composite material used.

Fatigue Test Specimens Preparation

The specimens were prepared according to ASTMD3479/D3479M–96, standard test method for fatigue of composite material .Fatigue specimens were cut in suitable dimensions to satisfy the machine test section that suited for flat plate specimens. Figure (3) shows the fatigue test specimen and its configuration.

Fatigue Tests

All fatigue tests were carried out in the laboratories of electromechanical engineering department, University of Technology using AVERY fatigue testing machine Type-7305.The experiments were conducted at room temperature and at stress ratios R=-1.

Corrosion Fatigue Test

Corrosion fatigue tests were performed in a 3.5% NaCl aqueous solution. The NaCl solution used in the present study was a 3.5% mass mixture of sodium chloride (NaCl) salt and distilled water corresponding approximately to the composition of salt water. The aerated solution was circulated from and to a reservoir via corrosion cell fitted on the specimen at room temperature. Each reservoir contained a liter of simulated sea water solution .The corrosion cell developed to conduct the aggressive environment test is shown in (figure 4).

RESULTS AND DISCUSSION

Tensile Test Results

Table (2) shows the experimental tensile strength of (carbon+ glass) fibers /PMMA , elastic modulus (E) was calculated by construct a secant between two point typically at strain values of 0.001 and 0.003 [12].

Fatigue Life Testing

Basquin s law may be used to express the relationship between the fatigue strength and fatigue life of the materials [13, 14]. This law is represented by an equation of the form.

$$s_f = AN_f^a \text{..........} \quad (1)$$

where (σ_f) is the cyclic stress amplitude at failure, N_f is number of cycles to failure, and (A) and (α) are the fitting parameters. If this is so, then a plot of log N_f versus log σ_f will be a straight line, the slope of which will give the value of constant α.The constant A can be determined using the equation for this straight line.

The data obtained from the fatigue tests were used to plot the graphs of the logarithm of fatigue life (log N_f) versus logarithm of stress amplitude (log σ_f).
The following equation can be obtained.

$$\sigma_f = 235 N_f^{-0.167} \quad \text{..........(2)}$$

The above empirical formula gives 16MPa fatigue endurance limit at 10^7cycles. In order to investigate the influence of corrosion on fatigue life, 12 specimens were tested to find the wohler curve under dry fatigue as a basic result for comparison with the corrosion – fatigue results .The experimental results are given in Tables (3),(4) and represented in figure (5)

Constant Corrosion-Fatigue Tests

12 specimens were tested under corrosion-fatigue interaction using 3.5%NaCl solution. The results are given in table (4).

The best fit for the above data gives the following relation

$$\sigma_f = 1360 N_f^{-0.334} \quad \text{...... (3)}$$

and the endurance limit at 10^7 is 6.24MPa.

From figure (5) it can be seen that the environment of 3.5% NaCl aqueous solution significantly decreases the fatigue life at constant loads, especially at lower stress amplitudes, which is consistent with the test results reported in references [15].

Variable Stress Corrosion – Fatigue Tests

Cumulative corrosion –fatigue tests were carried out under two block loading. The applied number of cycles is 10^4 cycles at either low and high stresses. Table (5) presents the cumulative corrosion – fatigue tests.

Fuqiang and Weixing [16] proposed a damge model for composite materials subjected to the constant fatigue loading as

$$D(n) = 1 - \left[1 - \left(\frac{n}{N_{f_i}} \right)^B \right]^A \quad \text{.........(4)}$$

Where: n is the applied cycle at stress level σ_i
N_f is the fatigue life at failure at stress level σ_i
A and B are model parameters and D (n) is the fatigue damage at constant loading,
Which equals zero when n = 0 and equal 1 when $n_i = N_{fi}$

For damage accumulation of composite materials which are subjected to variable amplitude fatigue loading, the cumulative fatigue damage, D (n_i) in the composite materials subjected to the i_{th} loading is calculated as [16]

$$D(n_i) = 1 - \left[1 - \left(\frac{n_i + n_{ij-1}}{N_{f_i}} \right)^{B_1} \right]^{A_1} \text{..........} \ (5)$$

Where n_i and n_{i-1} are the cycles under the i_{th} and $(i-1)_{th}$ cycling loadings, N_i and N_{i-1} are the fatigue life corresponding to the i_{th} and $(i-1)_{th}$ applied loadings . n_{ij-1} is the equivalent cycles under the i_{th} cycle loading. B_1 and A_1 are materials constants.
Following the work of ref [16], the proposed damage model may be written as

$$D(n) = 1 - \left[1 - \left(\frac{n}{N_{f_i}} \right) \right]^{a} \text{..........} (6)$$

Where α is the inverse slope of S-N curve, for the present work the slope of S-N curve equation is 0.334 and the total damage D_{total} may be equal the summation of damage at low stress level D_L and high stress level D_H ,where the number of blocks (program) till failure are equal to unity, then

$$D_{total} = D_L + D_H \text{..........} \ (7)$$

Applying equation (6) for low and high stress levels to the test data of table (5), the results become

$D_L = 0.1785$, $D_H = 0.5905$, So $D_{total} = 0.769$

Table (6) gives the results applying the present model in comparison with the experimental ones.

Predictions of the corrosion – fatigue life using the proposed model may still be considered to be reasonable if the deviation of the real life from the predicted life is no more than a factor 2.

Based on the proposed model which is an extension of the proposed model [16]. The predicted life show that the fatigue damage model is capable of describing the nonlinear damage evolution in the fatigue life period of the PMMA composite materials.

CONCLUSIONS

1- Fatigue properties of PMMA composite material, the fatigue strength reduced by 61% due to corrosion interaction.
2-A non linear damage model is applied in this study. This model is capable of describing the corrosion-fatigue damage evolution of composite material PMMA.
3- The two level loading examples shows that the model can predict corrosion-fatigue life of composite material quite well

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Table (1): Properties of Fibers and PMMA polymer used in this study[9 & 10].

Material	Young's modulus (MPa)	Tensile strength (MPa)	Elongation (%)	Density (g/cm^3)
Glass+Carbon	151000	3625	2.8	2.18
Perlon	3430	530-875	1-30	1.14
PMMA Polymer	2240	15-35	2.1	1.19

Table (2): Mechanical properties of composite material

Tensile Strength (MPa)	Young Modulus (MPa)	Elongation %
50	1075	5.23

Table (3): Basic S-N fatigue results at room temperature (RT).

Specimen No.	Stress (MPa) σ_f	N*f* (Cycles)	N*f* (Cycles) Average
1,2,3	40	46000,43000,40000	43000
4,5,6	30	200000,193000,187000	193333
7,8,9	25	800000,726000,664000	730000
10,11,12	20	2450000,2501288,2652566	2534618

Table (4): Constant stress corrosion-fatigue interaction results.

Specimen No.	Stress (MPa) (σ_f)	N*f* (Cycles)	N*f* (Cycles) Average
13,14,15	40	37000,40000,34000	37000
16,17,18	30	104000,102000,99000	101667
19,20,21	25	110000,142000,172000	141333
22,23,24	20	300000,307000,302799	303266

Table (5): Corrosion-cumulative fatigue damage results.

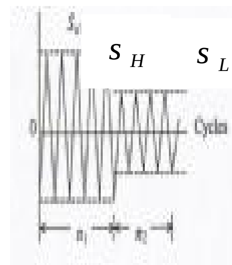
Specimen No.	Loading sequences (MPa)	Fatigue-corrosion life (cycles)	Average life (cycles)	Test program
25,26,27	25-40	55000,64800,71000	63600	 $n_1 = n_2 = 10^4$ cycles
28,29,30	40-25	44600,48000,37600	43400	

Table (6): shows the corrosion – fatigue damage and life for PMMA composite material .

Loading sequences (MPa)	$N_{f\ \mathrm{exp\ average}}$	$N_{f\ \mathrm{model}}$	$D_{\mathrm{total\ exp}}$	$D_{\mathrm{total\ model}}$	$D_{\mathrm{Palmgren\text{-}Miner\ (PM)}} = \sum \frac{n_i}{(N_f)_i}$ [17]
25-40	63600	35454	1.028	0.769	1
40-25	43400	35454	0.7019	0.769	1

(a) Mold with Fibers and Perlon +PVA. **(b) Resin transfer to the mold.**

Figure (1): Vacuum Molding Technique Used in this Study.

Figure (2- a) Tinius Olsen (H50KT) Test Machine.

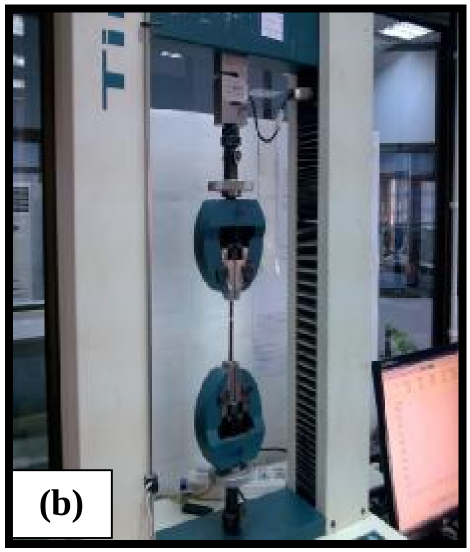


Figure (2-b) Close up of specimen fixture.

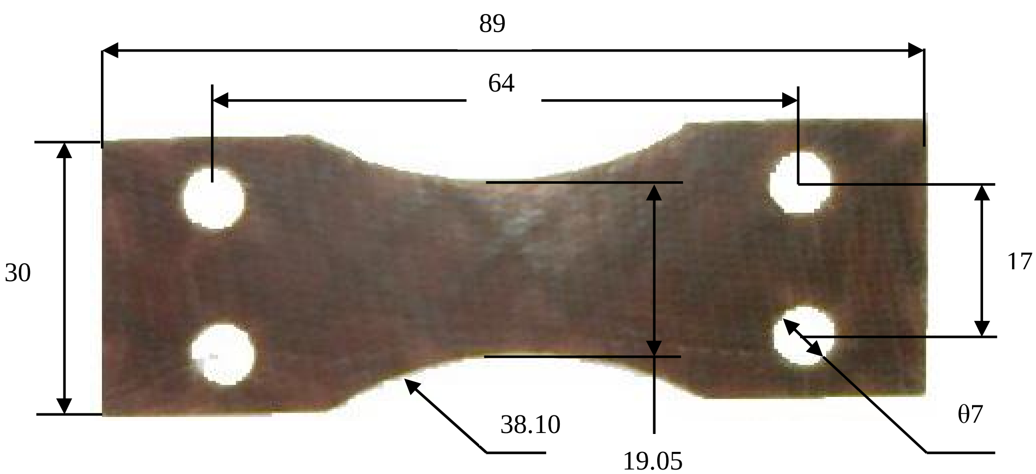


Figure (3) Fatigue specimen (all dimensions in *mm*) according to ASTMD3479/D3479M–96.

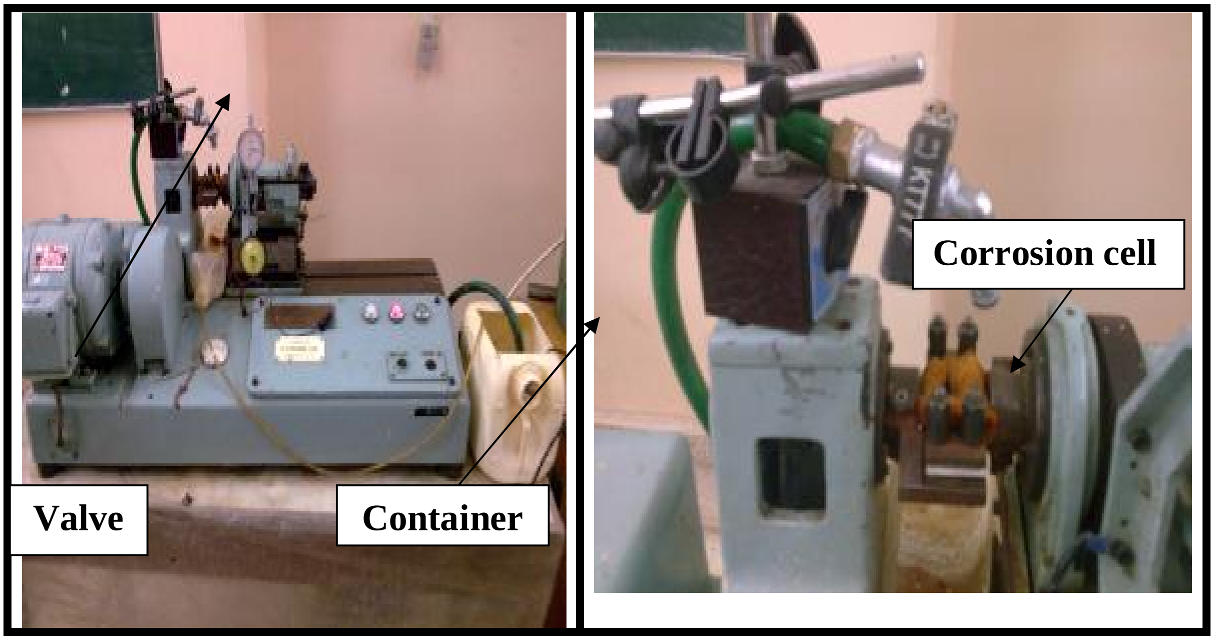


Figure (4): Corrosion –fatigue interaction test machine.

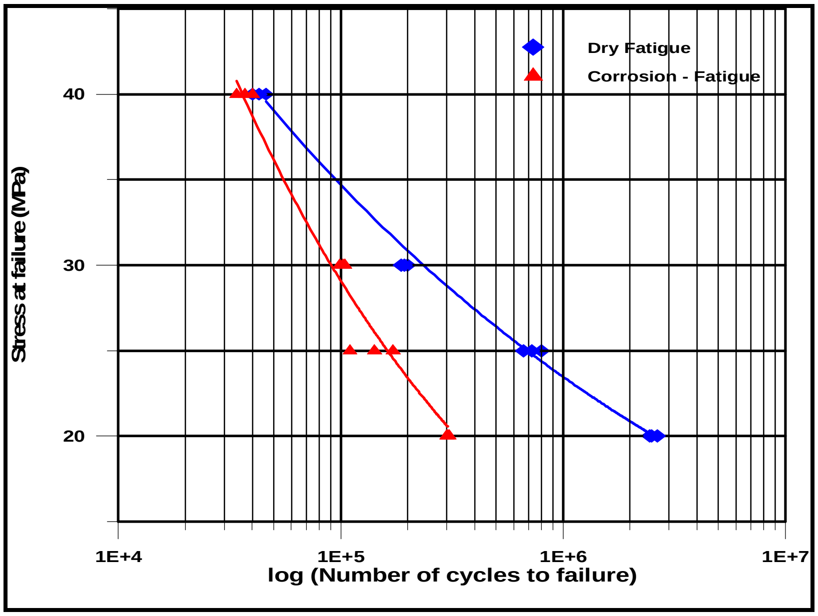


Figure (5): Fatigue and corrosion-fatigue behavior at constant loading