Journal of Engineering and Development
www.jead.org
Vol. 20, No.02, March 2016
ISSN 1813-7822

STRENGTH-CYCLE CURVES FOR MULTI-AXIAL FATIGUE OF POLYESTER REINFORCED BY GLASS FIBER

Dr. Samira Kareem Radhi[1], Dr. Ehsan Sabah Muhammed [2], *Karar Abd Al-Sahab Ali [3]

1) Assist Prof., Mechanical Engineering Department, Al-Mustansiriayah University, Baghdad, Iraq.
2) Assist Prof., Mechanical Engineering Department, Al-Mustansiriayah University, Baghdad, Iraq.
3) M.S.C student, Mechanical Engineering Department, Al-Mustansiriayah University, Baghdad, Iraq.

(Received: 23/03/2015; Accepted: 08/12/2015)

Abstract: This study discusses the development of a multi-axial fatigue testing machine, and studies the fatigue behavior of cantilever glass fiber composites beam under in phase bending-torsion dynamic loadings. The effect of bending–twisting deflections and the number of layers on the peak strength, fatigue life, and failure mechanisms are analyzed. Two types specimen (two dimension woven fiberglass (2D) and three dimension stitching fiberglass (3D)) are investigated. The results of both 2D and 3D show that the strength is increased significantly with increase bending-torsion stresses, while the damage becomes faster. The strength is reduced rapidly in about the first 30% of its fatigue life due to matrix cracking, which is then followed by a much slower rate of strength reduction until the failure. And the samples strength is increased as the number of layers increased by 20±3 % when tested under the same loading conditions. Furthermore the strength in 2D specimen is higher than the strength in the 3D specimen by about 20% when subjected to the same bending deflection-twisting angle. The fatigue life in 3D sample is greater than fatigue life in 2D samples by about 17% when tested under the same loading conditions.

Keywords: *combined fatigue, strength degradation, 2D &3D composite material*

منحنيات المقاومة- عدد الدورات لمادة البوليسترالمقوى بالألياف الزجاجية تحت تاثير الكلال متعدد المحاور

الخلاصة: يناقش هذا العمل انشاء جهاز اختبار الكلال متعدد المحاور ، ودراسة سلوك اجهاد الكلال في عتبة كابولية من المواد المركبة (الألياف الزجاجية) تحت تأثير أحمال ديناميكية في طور الانحناء - الالتواء. تم تحليل تأثير انحرافات الانحناء – التواء وعدد الطبقات على مقاومة العينات وعمر الكلال. تم اختبار نوعين من العينات (ثنائي البعد (2D) من الالياف الزجاجية المنسوجة وثلاثية البعد (3D) الألياف الزجاجية المخيطة. لوحظ في العينات من النموذجين زيادة المقاومة إلى حد كبير مع زيادة اجهاد التواء- انحناء، بينما يصبح الضرر أسرع. تنخفض المقاومة بسرعة في حوالي 30٪ من عمر الكلال للعينة بسبب التشققات التي تحصل في البوليمير، بعد ذلك تنخفض المقاومة بمعدل بطي جدا حتى الفشل. و زيادة مقاومة العينات عند زيادة عدد الطبقات بنسبة20±3% عند اختبارها تحت نفس

**Corresponding Author* Alikarar03@gmail.com

ظروف التحميل. وعلاوة على ذلك مقاومة في العينات ثنائية البعد (2D) أعلى من مقاومة العينات ثلاثية البعد(3D) بنحو 20٪. عمر الكلال في نموذج ثلاثي الأبعاد أكبر منه في عينات ثنائية البعد بنسبة 17 % عند اختباره بنفس الاحمال.

1. Introduction

In the engineering science, fatigue is defined as a process of cycle by cycle accumulation of damage in a material undergoing fluctuating stresses and strains. A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after a certain number of load fluctuations have been experienced as in [1]. While multi-axial fatigue is defined as a process of cycle by cycle accumulation of damage in a material undergoing two or more different type of fluctuating stresses and strains.

Multi-axial loadings can be classified as proportional (in-phase) and non-proportional (out-of-phase). During proportional loading the principal stress directions remain fixed in time and the principal stress ratio remains constant even though the loading directions rotate. As opposed to this, non-proportional loading is characterized by rotating principal directions and variable principal stress ratio.

Early multi-axial fatigue studies were primarily conducted using aluminum alloys, stainless steels, super alloys and steels. These choices were governed by the extensive use of these materials in fatigue critical components, e.g., pressure vessels, turbine blades, axles, bearings, and crankshafts, which are subject to multi-axial cyclic stresses and strains as in[2]

Fiber-reinforced composites are extensively used in manufacturing of various components in engineering structures such as high-pressure vessels, aerospace structures, transmission shafts in automobiles, support structures, etc. Traditional materials are being replaced by composites due to their high strength to weight ratio, corrosion resistance, and cost. The increasing use of composite structures has highlighted the need for models to determine the monotonic and fatigue characteristics of composites under multi-axial stress fields. Many multi-axial fatigue damage models based on strain, stress, and energy data have been proposed in an attempt to correlate the data with fatigue life. However, a general theory capable of modeling the fatigue life of a variety of materials subject to different loading conditions is not available as in[3].
Soon-Bok Lee ,[4]developed a deflection controlled multiaxial fatigue testing machine to produce multiaxial cyclic loadings with variable speed on a cantilever type specimen, by applying bending moments and twisting moments at the same frequency but with adjustable phase angle, amplitudes, and mean values.

M.Elhadary [5]investigated a new failure criterion for GFRP composite materials. Experimental fatigue tests were conducted on thin-walled tubular specimens woven-roving glass fiber reinforced polyester (GFRP), with 0^o, 45^o and 90^o phase shift between bending and torsional moments for two fiber orientations, ([±45]2 and [0,90]2), at different negative stress ratios,(R = -1, -0.75, -0.5, -0.25, 0). A new term was introduced to the Tsai-Hahn criterion to govern the fatigue behavior of the tested specimens.

M. BOBYR , et al. [6] proposed a life prediction approach for a random multiaxial fatigue(tension-compression, torsion) . The investigation of the non-proportional low cycle fatigue life of D16T aluminum shows small additional damage stress, and also develop energetically damage model for complex non-proportional stress state during low-cycle fatigue for construction.

Ying-Yu Wang, et al. [7] reviewed multi-axial fatigue criteria. The criteria are divided into three groups, according to the parameters used to describe the fatigue life or fatigue strength of materials. They are stress criteria, strain criteria and energy criteria. Their predictive capabilities are checked against the experimental data of different materials lake [1045HR steel and 304 stainless steel] under proportional and non-proportional loading.

Ahmed M. El-Assal, et al.[8] investigated fatigue behavior of unidirectional glass fiber reinforced polyester (GFRP) composites at room temperature under in-phase combined torsion/bending loading. Constant-deflection fatigue machine with frequency of 25 Hz is used to carry out all fatigue tests. The results showed that, the unidirectional glass fiber reinforced polyester composites have poor torsional fatigue strength compared with the published results of pure bending fatigue strength. Endurance limit value of GFRP specimens tested under combined torsion/bending loading equals 8.5 times the endurance limit of pure torsion fatigue. On the other hand the endurance limit of combined torsion/bending fatigue strength approximately half the fatigue limit of pure bending fatigue strength.

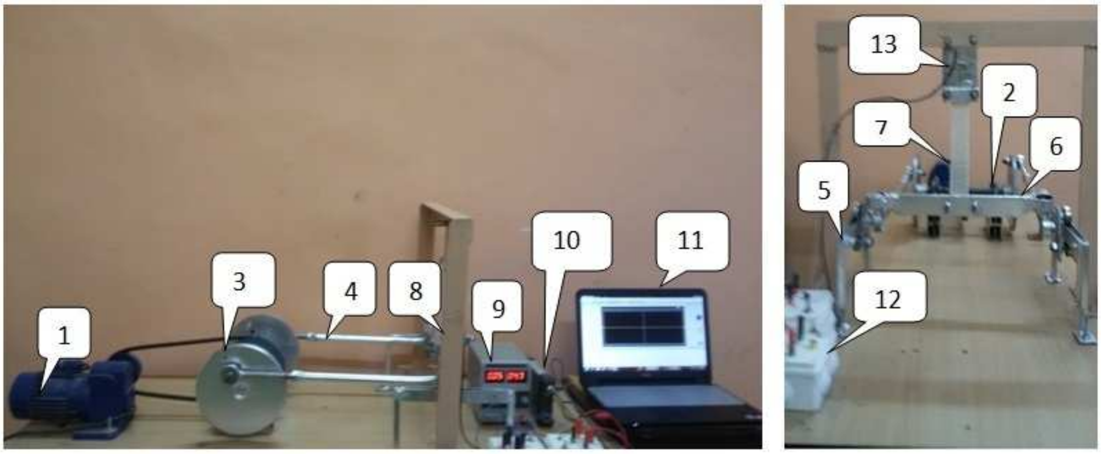
C. Capela,et al [9] studied the fatigue behavior of tubular carbon fiber composites under in phase biaxial bending/torsion dynamic loadings. Both the torsion stress and mean stress effects on the fatigue strength and failure mechanisms was analyzed. Fatigue strength decreases significantly with increased torsional/bending stresses ratio, while the damage becomes faster. The increase of stress ratio from 0 to 0.3 promotes significant decrease of the fatigue strength for bending/torsion loading.

The aim of this study is to design and manufacture a device to investigate the behavior of 2D and 3D composite material under bending-torsion fatigue loads.

2. Development of the multi-axial machine

2.1 Construction

The multi-axial fatigue machine used by the previous works depends on utilizing one form or another of expensive high-accuracy servo-hydraulic actuators. In this study, the machine is designed by using a simpler and cheaper crank wheels mechanism to apply simultaneous bending and torsion load to cantilever specimen. The machine consists of an electrical motor, operation shaft, two crank wheels, two connecting rods, two guides and cross beam as shown in Fig. (1).



(A)Front view (B) Side view

Figure1.multi-axial fatigue testing machine.(1. Motor, 2. Operation Shaft, 3. Crank Wheel, 4.Connecting rod, 5. Guide , 6. Cross beam, 7. Specimen,8. Frame, 9. Power Supply,10. Oscilloscope, 11. Computer, 12. Amplifier, 13. Strain Gage)

The (0.25hp) motor rotates at (2730 r.p.m) and, the motor is interleaved with gear box with gear ratio (16:1) . The rotating speed reaches the operation shaft reduced to (110 r.p.m) by means of pulleys and belt drive. Then, the crank wheels, connecting rods, and cross beam assembly convert the rotational motion of the motor to simultaneous bending and twisting deflection on specimen. The bending and twisting deflection are adjustable by the two crank wheels.

2.2Measurement system

The measurement system consists of four strain gages which are arranged in two half Wheatstone bridge circuits, one for measuring bending load and the other circuit to measure torsion load, each circuit is connected to an amplifier. The amplifier is used to magnify the output signal of Wheatstone bridge. Figure (2) shows the circuit of the amplifier used in this study. The output of the amplifier is then feed to the oscilloscope.

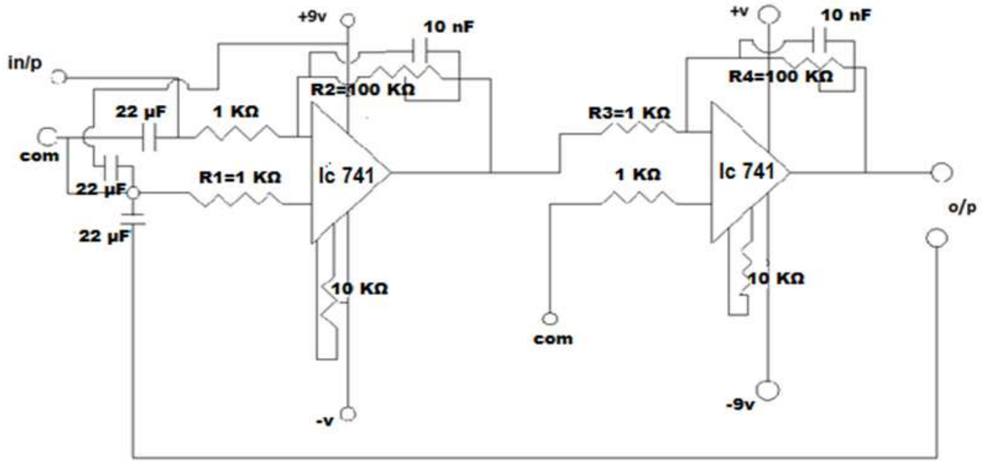


Figure 2. Amplifier circuit

3. Material and specimen

Two groups of fiber glass / polyester composite specimens are prepared. The first group is 2D woven fiber glass / polyester and the second group is 3D stitching fiberglass/polyester. Four and six layers (2.6 mm and 3.8 mm thickness) 2D woven as well as three and five (2.6 mm and 3.8 mm thickness) layers of 3D stitching specimens. The dimensions of specimen are shown in figure (3).

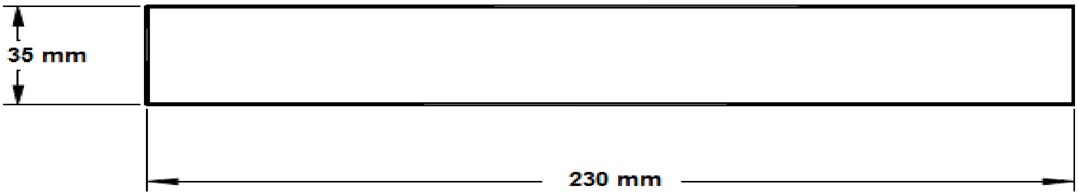


Figure 3. Specimen's geometry

All specimens tested under different loading condition are summaries in Table (1).

Table 1. Specimen's specifications

Specimen no.	*Woven type*	*Number of layers*	*Modulus of elasticity (Gpa)*	*Deflection value*	*Twisting angle*
Sample1	2D	4	9	30 mm	3.719°
Sample2	2D	4	9	40mm	5.739°
Sample3	2D	4	9	50mm	10.117°
Sample4	2D	6	9	30mm	3.719°
Sample5	2D	6	9	40mm	5.739°
Sample6	2D	6	9	50mm	10.117°
Sample7	3D	3	7.281	30mm	3.719°
Sample8	3D	3	7.281	40mm	5.739°
Sample9	3D	3	7.281	50mm	10.117°
Sample10	3D	5	7.281	30mm	3.719°
Sample11	3D	5	7.281	40mm	5.739°
Sample12	3D	5	7.281	50mm	10.117°

4. Results and discussion

This section shows the fatigue results obtained under bending-torsion cyclic loadings. The simultaneous bending stress amplitude σ_a, the shear stress amplitudeτ_a andthe equivalent stress amplitude SALT were calculated using Equations. (1), (2) and (3), respectively [10]:

$$\sigma_a = \frac{6M_B}{b\,t^2} \quad (1)$$

$$\tau_a = \frac{T}{K_1 b t^2} \quad (2)$$

$$\text{SALT}=\sqrt{\sigma_a{}^2 + 3\tau_a{}^2} \quad (3)$$

Where M_B is the bending moment , T is the torsion moment, b & t are the width and thickness of specimen, respectively, andk_1 is a constant, its value depends on the ratio ***b* / *t*** can be obtained from standard tables.

4.1 Effect of combined (bending-twisting) deflection

The behavior of strength degradation versus number of cycles for 2D woven four layer and 3D three layers specimens subjected to three different bending-twisting deflection is indicated in Fig (4) and Fig(5)respectively. It can be seen that the strength is decreased with increasing the number of cycles. The strength is decreased rapidly at the first 30% of its fatigue life due to matrix cracking, which is then followed by a much slower rate of strength reduction until the failure occurs. Furthermore the strength is increased with increasing of the bending deflection and twisting angle. The peak strength, number of cycles, and strength degradation ratio (ratio between the upper strength and lower strength in the same sample) are shown in table (2) for all specimen.

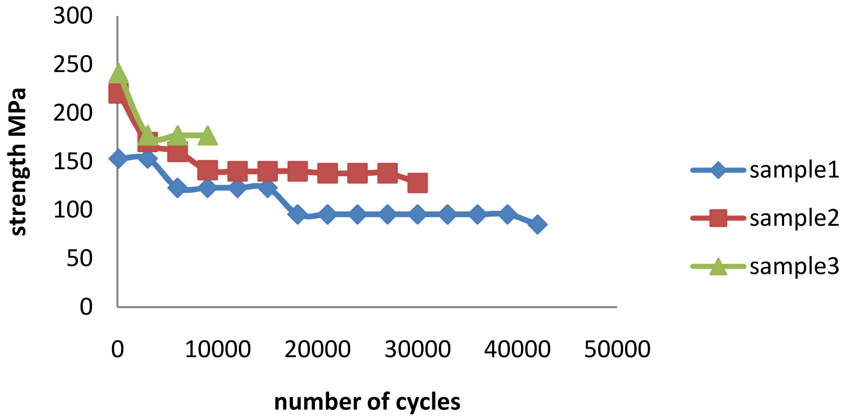


Figure 4. Experimental strength behavior versus number of cycles (2D).

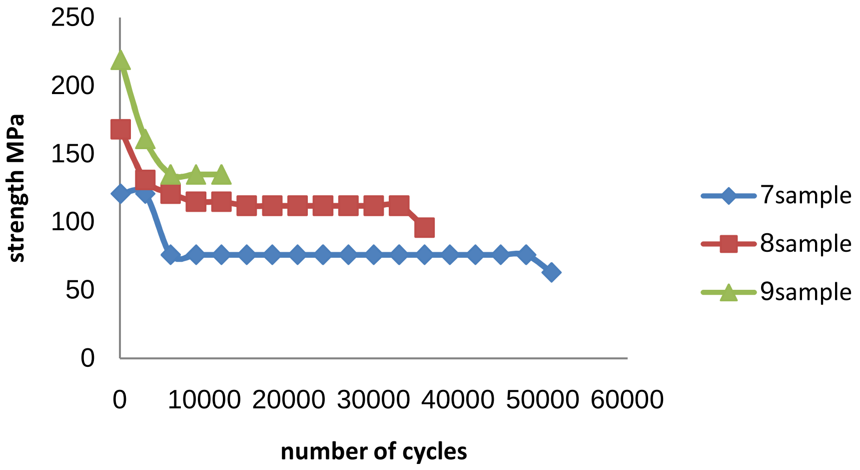


Figure 5. Experimental strength behavior versus number of cycles (3D).

Table 2.Summary of tested specimens

Specimen no.	*Woven form*	*Number of layers*	*Bending- Twisting deflection*	*Peak strength Mpa*	*Fatigue life*	*Strength degradation ratio*
Sample1	2D	4	30mm-3.72˚	152.73	43000	37.55%
Sample2	2D	4	40mm-5.74˚	220	30000	36.36%
Sample3	2D	4	50mm-10.117˚	241	10000	26.55%
sample4	2D	6	30mm-3.72˚	167	30000	25.14%
Sample5	2D	6	40mm-5.74˚	228	20000	25.21%
Sample6	2D	6	50mm-10.117˚	256	6000	23.82%
Sample7	3D	3	30mm-3.72˚	120.7	51000	37%
Sample8	3D	3	40mm-5.74˚	168	36000	33.33%
Sample9	3D	3	50mm-10.117˚	219	12000	38.35%
Sample10	3D	5	30mm-3.72˚	138	36000	30%
Sample11	3D	5	40mm-5.74˚	196	25000	31.12%
Sample12	3D	5	50mm-10.117˚	227	7000	26.43

4.2. Effect of number of layers on strength degradation

In this section, a comparison between the behavior of 2D four layers and 2D six layers specimen is shown in Fig (6). Also a similar comparison is shown in Fig (7) between 3D three layers and 3D five layers specimen when tested under the same loading condition. It can be observed for both the 2D woven and 3D woven samples, that the strength developed in samples is increased by 20±3 % as the number of samples layers increased. This increase in strength is occurring due to increase in the fiber content 2D six layers and 3D five layers specimen. Moreover the life in the 2D six layers is less than the life in 2D four layers, this is because the strength degradation ratio is lower in 2D six layers and this means that the operating stress is higher in 2D six layers so that the life is decreased. A similar behavior is shown in 3D five layers specimen.

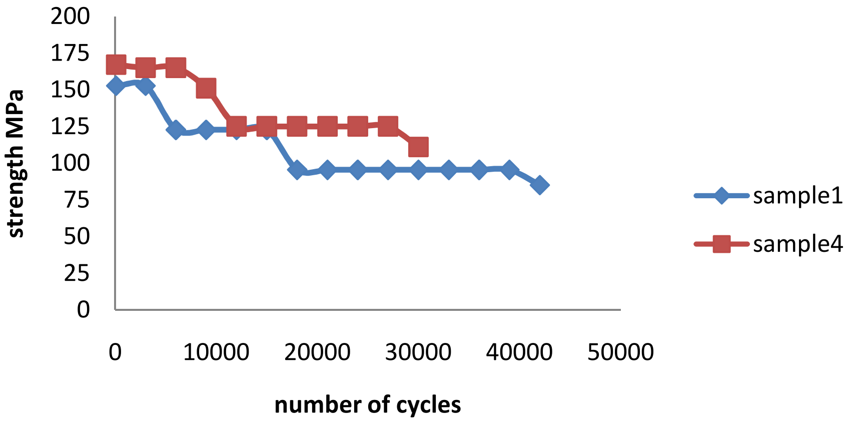


Figure 6.Comparison between strength degradation of 2D four layers and 2D six layers specimen subjected to 30mm bending deflection -3.719˚twisting angle.

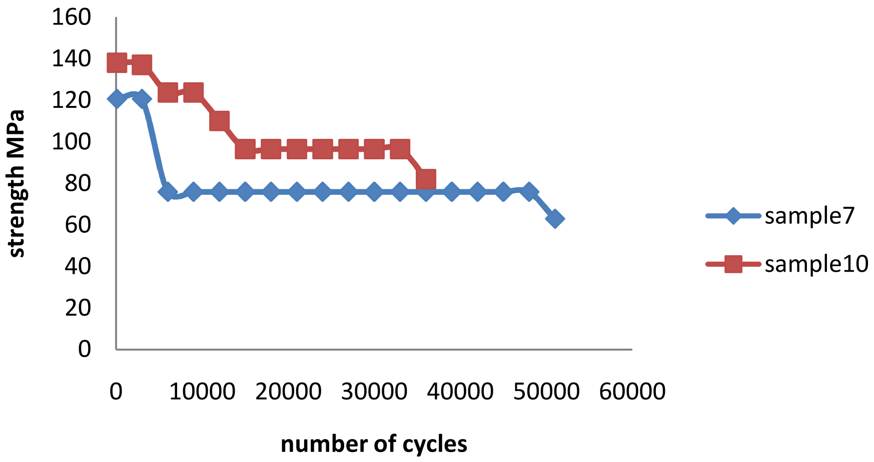


Figure 7.Comparison between strength degradation of 3D three layers and 3D five layers specimen subjected to 30mm bending deflection -3.719˚twisting angle.

4.3. Effect of Woven Types on Strength Degradation Behavior

Figures (8&9) show comparison of strength variation versus the number of cycles between 2D and 3D woven composite.

It is clear that the strength in 2D specimen is higher than the strength in the 3D specimen by about 20% when subjected to the same bending deflection-twisting angle. The main reason of strength reduction in 3D composite is the reduce in volume fraction in 3D sample. The second reason is the damage and fabric distortion which are caused as the needle penetrates the fabric. Also the presence of the stitch thread and the distortion in the fabric causes a resin-rich pocket to be formed within the composite. This pocket can act as a potential crack initiator [11]. On the other hand the life of 3D sample is higher than the life of 2D sample by about 17% due to stitching improved the inter laminar fracture properties of the 3D samples.

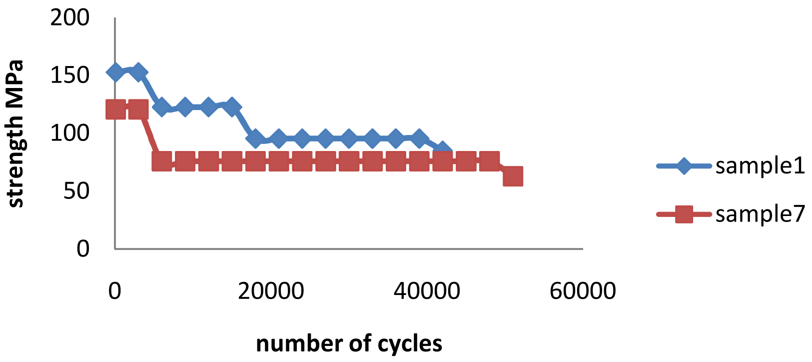


Figure 8.Comparison between strength degradation of 2D four layers and 3D three layers specimen subjected to 30mm bending deflection- 3.719˚ twisting angle.

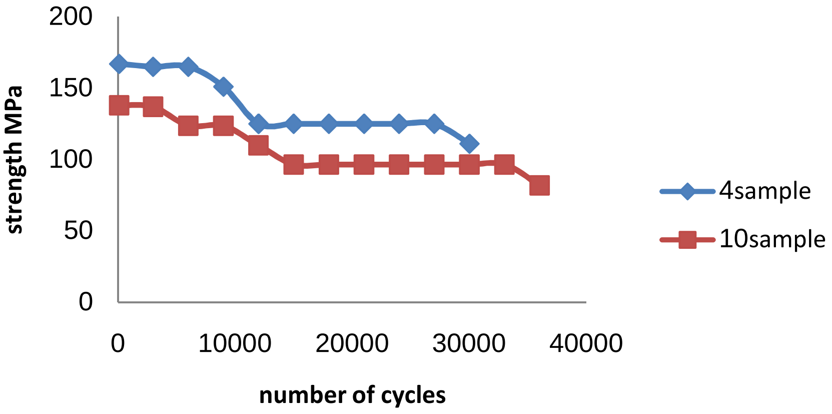


Figure 9.Comparison between strength degradation of 2D six layers and 3D five layers specimen subjected to 30mm bending deflection- 3.719° twisting angle.

4.4. Comparison between Theoretical and Experimental Results

The multiaxial loading effect on the fatigue strength is predicted using the Wear out residual strength model (equation (4)) which is developed by Christos kassapoglou criterion [12]:

$$\sigma_r = \sigma^{\frac{n}{N-1}} \sigma_{fs}^{\frac{N-n-1}{N-1}} \qquad (4)$$

whereσ is the applied stress,σ_{fs} is the static strength and N is the cycles to failure when σ is applied

The theoretical strength can be calculated by substituting the values of experimental applied stress and static strength in equation (4). The experimental and theoretical strength behavior for the 2D samples are shown in the fig (10) .It can be observed that the theoretical results are in a good agreement with the experimental results.

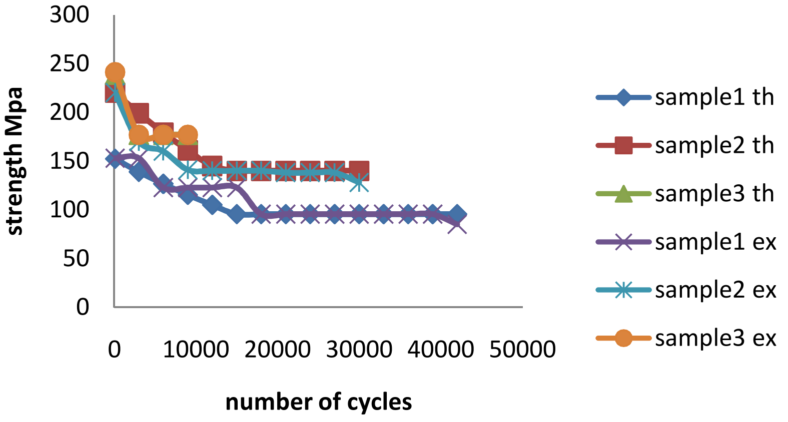


Figure 10. Comparison between theoretical and experimental results for 2D woven four layer specimen.

5. Conclusions

The main conclusions are:

- The load required to maintain the constant displacement on the specimen is decreased as the number of cycles increase.
- The strength reduced rapidly in about the first 30% of its fatigue life, which is then followed by a much slower rate of strength reduction until the failure occurs.
- It can be observed for both the 2D and 3D woven samples, that the strength is increased by 20±3 % as the number of layers increased.
- The strength degradation ratio increase as the number of layers decrease.
- The strength in 2D specimens are greater than those for 3D by about 20% when subjected to the same loading condition.
- The fatigue life of 3D specimens is higher than the life of 2D specimen by about 17%.
- The strength results of the theoretical model showed acceptable agreement with experimental results.

6. References

1. Mika Bäckström , (2003) “*Multiaxial Fatigue Life Assessment of Welds Based on Nominal and Hot Spot Stresses VTT Industrial Systems*” Thesis for PHD degree, Lappeenranta University of Technology (Lappeenranta, Finland) On the 13th of August.

2. D. F. Socie and G. B. Marquis (2000) “*Multiaxial Fatigue*” SAE, Warrendale, PA.

3.N. H. Yang, H. Nayeb-Hashemi, and A. Vaziri (2007)*”Multi-Axial Failure Models for Fiber-Reinforced Composites”*Journal of ASTM International, Vol. 4, No. 2 Paper ID JAI100533 Available online at www.astm.org

4.Soon Bok Lee , (1990)*”Development of A Deflection Controlled Multiaxial Fatigue Testing Machine”* KSME Journal, Vol. 4, No.2, pp. l03~108.

5. M.Elhadary(2013) *“A New Failure Criterion For GFRP Composite Materials Subjected To In-Phase and Out-of-Phase Biaxial Fatigue Loading Under Different Stress Ratios”*International Journal of Scientific & Engineering Research, Volume 4, Issue 9, September-2013 ISSN 2229-5518

6. M. Bobyr, B. Yakhno - E. Rusinski, P. Harnatkiewicz(2008)*“Damage in the complex low-cycle fatigue”*Archives of Civil and Mechanical Engineering Vol. Viii 2008 No. 3

7. Ying-Yu Wang, Wei-Xing Yao (2004) *“Evaluation and Comparison of Several Multiaxial Fatigue Criteria”* International Journal of Fatigue 26 ,17–25

8.Ahmed M. El-Assal , U.A. Khashaba*” Fatigue Analysis of Unidirectional GFRP Composites Under Combined Bending And Torsional Loads* ”composite structures 79 (2007) 599–605.

9. C. Capela , J.A.M. Ferreira, T. Febra , J.D. Costa (2015)*“fatigue strength of tubular carbon fibre composites under bending/torsion loading”* International Journal of Fatigue 70, 216–222.

10. E. J. Hearn (2002)“ *Mechanics of Materials*”, third edition 2000, ISBN 0 7506 3265 8.
11. Liyong Tong, Adrian P. Mouritz, Michael K. Bannister *“3D Fiber Reinforced Polymer Composites”* Elsevier Science Ltd.
12. Christos Kassapoglou (2012),*“Predicting the Structural Performance of Composite Structures under Cyclic Loading”* PhD thesis, Massachusetts Institute of Technology, Cambridge MA, USA