Fatigue life and strength of two composite materials used for below knee prosthesis

Vida útil y resistencia a la fatiga de dos materiales compuestos utilizados para prótesis debajo de la rodilla

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Abstract

Introduction. The composite materials (4P+2C) and (4P+4C) that are used in manufacturing the below knee prostheses socket were subjected to mechanical tests tensile and bending constant and variable loading at stress ratio R = -1 and room temperature (RT25-30°C). During the gait cycles, fatigue tensile and compression stress are induced.
Methodology. The thickness and weight of the fatigue samples were 2 and 2.7 mm, 2.954 and 3.42 (gm) respectively. The increase in thickness and weight showed an increase in (UTS)tensile (UTS) bending, ET modulus of elasticity in tensile and Eb modulus of elasticity in bending by 18.84% 7.72%, 36.36% and 15.06% respectively.
Results: While this increase improved the fatigue strength at 106 cycle and fatigue life at 60 MPa applied stress by 82.9% and 78.88% respectively. Increasing and decreasing fatigue variable program was carried out for the two composites.
Discussion. Applying Miner rule to the obtained experimental results showed that Miner theory is not capable to predict safe fatigue life and its overestimated the fatigue properties.
Conclusions. Proposed non-linear fatigue model was suggested and it applied to the experimental data. The fatigue results obtained from this model have a good agreement with those obtained experimentally

Keywords

Constant fatigue, variable fatigue, composite material, Miner rule, proposed model, below knee prosthesis socket.

Resumen

Introducción: Los materiales compuestos (4P+2C) y (4P+4C) que se utilizan en la fabricación del encaje protésico transtibial fueron sometidos a ensayos mecánicos de tracción y flexión bajo cargas constantes y variables, con una razón de esfuerzo R = -1 y a temperatura ambiente (RT 25-30 °C). Durante los ciclos de la marcha, se inducen esfuerzos de tracción y compresión por fatiga.
Metodología: El espesor y el peso de las probetas de fatiga fueron de 2 y 2,7 mm, y 2,954 y 3,42 g respectivamente. El aumento en el espesor y el peso mostró un incremento en la resistencia última a la tracción (UTS), en la resistencia a la flexión, en el módulo de elasticidad a tracción (Et) y en el módulo de elasticidad a flexión (Eb) de 18,84%, 7,72%, 36,36% y 15,06% respectivamente.
Resultados: Este aumento mejoró la resistencia a la fatiga a 10^6 ciclos y la vida a fatiga a una tensión aplicada de 60 MPa en un 82,9% y 78,88% respectivamente. Se llevó a cabo un programa de fatiga variable ascendente y descendente para los dos compuestos.
Discusión: La aplicación de la regla de Miner a los resultados experimentales obtenidos mostró que la teoría de Miner no es capaz de predecir una vida a fatiga segura y sobrestimó las propiedades a fatiga.
Conclusiones: Se propuso un modelo no lineal de fatiga, el cual se aplicó a los datos experimentales. Los resultados de fatiga obtenidos con este modelo mostraron una buena concordancia con los obtenidos experimentalmente.

Palabras clave

Fatiga constante, fatiga variable, material compuesto, regla de Miner, modelo propuesto, encaje de prótesis por debajo de la rodilla.

Introduction

Prostheses for wounded soldiers in the first world war were made of leather and wood. Today, they are characterized by materials with different properties. Metals such as titanium, aluminum and steel are used for their strength and lightness. In reality, they are alloys of stainless steel, nickel-titanium, etc. But new materials such as carbon fiber (C), kevlar (K), glass fiber (G), perlon (P), composite materials, silicones, etc. (Estillore et al. 2021) have also made their appearance, and have greatly modified the performance of patients.

Figure 1. Prosthetic limb parts

The socket connects the prosthesis to the amputated limb, Fig. 1. It is the base to which the prosthesis components are attached providing support for the stump and transmitting energy from the body to the artificial limb. It can be made from a composite material called "tubular carbon". These are carbon fibers impregnated with acrylic resin. Other composites include Kevlar, glass or carbon fibers, all of which are biocompatible, making the prosthesis lighter and more aerodynamic. The socket is custom-designed to prevent any movement of the stump within the socket.

In recent years, diverse prosthetic sockets have been developed and manufactured (Vitali et al., 2017 ; Marable et al., 2020, Kadhim et al., 2020 ; Zhang et al. 2021 ; Shastry et al. 2021 , Krishnan et al. 2024). In many cases of these developed prostheses, great attention has been paid to the used material and its mechanical characterization under static, fatigue and impact conditions. Composite laminate materials are extensively used in socket prostheses production in rehab centers due to their high strength/weight ratio, reliable and comfort. A number of studies have been carried out on the mechanical characterization of materials used in prosthetic sockets. Most of these labors can be divided into four clusters: synthetic fiber-reinforced composites (SFRC), natural/hybrid fiber-reinforced composites (NHFRC), CNT-reinforced composites (CNTRC) and 3D printing (3DP).

In the first research group, SFRC, we find the work Abbas et al (2020) where five composite laminates were examined for a total of 12 layers formed from different stratification of P, C, G and K. The laminates are formed, in addition to 8P, of: (4G), (4C), (2C+2G), (2G+2K) and (2C+4K). Fatigue tests were carried out at constant or variable amplitude. In Abbas et al (2020b)*10*, two composite laminates were used for a total of 8 layers; (8C) and (8P). Tensile and fatigue tests at constant amplitude were performed. Numerical simulations were also carried out using ANSYS. In Al-Waily et al. 2020 , four composite laminates were used for a total of 12 layers formed from different stratification of P, C, G and K. The laminates are made up of: (8P+2G+2K), (8P+2C+2G), (8P+2C+2K) and (6P+2C+4K). The various composites were reinforced with nanoparticles at different volume fractions. Tensile and fatigue tests were carried out at constant or variable amplitude. In (Nagarajan et al. 2023) , the authors studied the feasibility of PET fiber-reinforced woven and knitted composites for prosthetic sockets. To assess their mechanical properties, these composites were tested in laminate and socket form. For 3DP research group, there is the work of van der Kadhim et al. (2019), investigated the tensile and fatigue properties of a number of materials suitable for 3D printing: Novamid 1030-CF10, PA6/66-CF20, PLA-HI-GF10, PET and Tough PLA. They concluded that the last material is the most suitable according to ISO 527 testing. Oleiwiet al. 2022, tested prosthetic sockets were 3D printed for ultimate strength. Two different PLA from diverse manufacturers are used. Hamad et al. (2023), fifteen 3D-printed socket PLA reinforced with different materials of, C, K, G and cement are made-up. attention was focused on the mechanical behavior and microstructural of the sockets.

This work is part of the first group of studies on SFRCs for prosthetic sockets. Only two types of fiber are considered in this work; C and P. Based on these two fibers, two original laminates were developed and analyzed: 4P+2C and 4P+4C. Both laminates are mechanically characterized by tensile, bending and fatigue tests with constant and variable amplitude. The fatigue life and strength of below knee prosthetics under variable loads is prominent concern. Therefore, comprehensive research is necessary to estimate the fatigue properties of prosthetic sockets, considering the random loads experienced during real-life usage. The aim of this work is to find out which laminate to be used in the manufacture of the prosthetic sockets with good strength and durability, high efficiency and low cost. This work provides insights for prosthetic design and improve the durability and reliability of below knee prosthetics. The findings will contribute to improving the design and development of prosthetic devices.

In the second research group, NHFRC, we found the work of Sakuri et al. 2020, three laminates of 8 layers each were investigated in tension and fatigue. The three layers are formed from different combinations of P, C, G and bamboo (B). The laminates are: (6P+2G), (6B+1G+1C) and (6B+2C). In Oleiwi et al. 2022[14], seven composite laminates were made from a polyester resin matrix reinforced with: G, C, P and Jute (J) with a number of layers ranging from 5 to 11. The laminates are formed, in addition to 4P, of: (1J), (2J), (3J), (2C,3J), (4C,3J), (2G,3J) and (4G,3J). Three-point bending, shear and impact tests were performed on these laminates. The same composite laminates were considered in Hamad et al. 2023[15] with tensile tests and density measurements. the authors examined the mechanical behavior of a composite formed from degradable natural fiber, Cantala fiber (CF), with an unsaturated polyester matrix and microcrystalline cellulose for prosthetic socket. In Faheed et al. 2022 , the authors also used natural fibers for prosthetic socket, sisal (S) and cotton natural fibers (CO). Ten laminates were tested, with layer counts ranging from 5 to 9. The laminates are made up of more than 4P of different layers of CO, S, G and C. Tensile tests were carried out and simulation are done using ANSYS.

In the third research group, CNTRC, on find the work of Abubakre et al. 2023 where the authors present a literature review of recent studies on rubber and carbon nonotube (CNT) reinforced polymer (nano)composites. In Gariboldi et al 2023 , the authors set up a test procedure to assess the mechanical strength of lower-limb prosthesis sockets. Twenty-three sockets were fabricated from the same identical plaster model using the resin-infusion lamination technique. Each socket presented a different combination of three parameters; stratigraphy, distal adapter and resin.

For 3DP research group, there is the work of van der Stelt et al. 2022 , investigated the tensile and fatigue properties of a number of materials suitable for 3D printing: Novamid 1030-CF10, PA6/66-CF20, PLA-HI-GF10, PET and Tough PLA. They concluded that the last material is the most suitable according to ISO 527 testing. Marinopoulos et al. 2022 and Alwin et al, 2023, tested prosthetic sockets were 3D printed for ultimate strength. Two different PLA from diverse manufacturers are used. Ramlee et al. 2024 , fifteen 3D-printed socket PLA reinforced with different materials of, C, K, G and cement are made-up. attention was focused on the mechanical behavior and microstructural of the sockets.

This work is part of the first group of studies on SFRCs for prosthetic sockets. Only two types of fiber are considered in this work; C and P. Based on these two fibers, two original laminates were developed and analyzed: 4P+2C and 4P+4C. Both laminates are mechanically characterized by tensile, bending and fatigue tests with constant and variable amplitude. The fatigue life and strength of below knee prosthetics under variable loads is prominent concern. Therefore, comprehensive research is necessary to estimate the fatigue properties of prosthetic sockets, considering the random loads experienced during real-life usage. The aim of this work is to find out which laminate to be used in the manufacture of the prosthetic sockets with good strength and durability, high efficiency and low cost. This work

provides insights for prosthetic design and improve the durability and reliability of below knee prosthetics. The findings will contribute to improving the design and development of prosthetic devices.

Method

Theoretical consideration

The main parameter for fatigue design is the establishing the S-N curve by testing standard specimen under numbers of stress or strain levels. The S-N curve determines the relationship between stress applied (σf) and number of cycles to failure (Nf).

$$\sigma_f = A\, N_f^{\alpha} \tag{1}$$

where A and α are material constants, which can be obtained by

$$\alpha = \frac{H \sum \log \sigma_f \log N_f - \sum \log \sigma_f \sum \log N_f}{H \sum (\log N_f)^2 - [\sum \log N_f]^2} \tag{2}$$

$$logA = \frac{\sum \log \sigma_f - \alpha \sum \log N_f}{H} \tag{3}$$

In where H is the number of stress levels that were chosen for testing. When it comes to buildings that are put through fluctuating load cycles while in operation, it is possible that it would be preferable for fatigue failure to never take place. It has the implication that the fatigue limit or endurance fatigue limit should not be exceeded by any of the cycles of the load spectrum for any of the loads. After that, the challenge of prediction is narrowed down to the prediction of the endurance exhaustion limit. The primary objective of this study is to conduct experiments with the purpose of identifying a composite material that is acceptable for use in a variety of service conditions and possesses both high strength and a long lifespan.

Variable amplitude test

The well-known theory for variable loads is the Miner rule on the linear cumulative damage; Miner 1945*23*. Miner suggested that fatigue failure occurs at the moment that

$$\sum \frac{n_i}{N_{fi}} = 100\%\ for\ more\ than\ two\ blocks \tag{4}$$

Miner found that the values of $\sum \frac{n_i}{N_{fi}}$ varying from 0.61 to 1.45, but average reasonably close to unity. since that time, the rule $\sum \frac{n_i}{N_{fi}} = 1$ has frequently been quoted as the Miner rule. Miller et al. 1986*24* suggested a cumulative fatigue damage model taking into account the effect of loading sequences, the material properties and constants of the S-N curve equation.

$$Damage\ (D) = \frac{\left(\sigma_H^{1-1/\alpha} - \sigma_L^{1-1/\alpha}\right) N_{fc}\, A^{1/\alpha}}{(\sigma_H - \sigma_L)(1 - 1/\alpha)} \tag{5}$$

$$N_{fc} = \frac{D(1 - 1/\alpha)(\sigma_H - \sigma_L)}{\left(\sigma_H^{1-1/\alpha} - \sigma_L^{1-1/\alpha}\right) A^{1/\alpha}} \tag{6}$$

where Nfc is the number of cycles at failure for cumulative fatigue, σH is the high stress level and σL is the low stress level.

Experimental work

The composite materials which are employed to manufacture the prosthetic socket is illustrated in Table 1. The details of the preparation the raw materials for socket can be found in the Books of ASTM D638-14*25* Standard. In this work two samples were selected as given in Table 1.

Table 1. Composite materials used in prosthetic socket

Sample	Lamination	Perlon	Fiber carbon
4P+2C	4 Perlon layers +2 carbon	70%	30%
4P+4C	4 Perlon layers +4 carbon	50%	50%

The main mechanical tests done for the above materials are: tensile, bending and fatigue under constant and variable loading.

Tensile test

The purpose of this test is to obtain the main mechanical properties, like ultimate tensile strength (UTS), modulus of elasticity (E). The tensile specimens were designed and manufactured according to ASTM standard and ASTM D638-14*25* as illustrated in Fig. 1 Three samples, for each test were used and the average was recorded.

Figure 1. Specimen tensile test

All tensile tests were done using a Computer Controlled Electronic Universal Testing, Tinus Olsen, with 1 mm/sec speed. Fig. 2.

Figure 2. Tensile Test rig

Bending test

The main purpose of this test is to obtain the bending-modulus of elasticity (Eb) which is to be applied to obtain the alternating stress (σa) in analysis of fatigue results. The bending sample are made according to the Standard Specification ASTM(D790-*17*)*26*. Fig. 3. shows the profile and dimensions of the bending specimen. However, the standard bending test sample with the test rig are presented in Fig. 4.

Figure 4. Bending test Machine and actual specimen: (a) Bending test machine (b) bending specimen

Fatigue test

The fatigue properties such as stress at failure (σf) and Number of cycles to failure (Nf) to design the S-N curve and the cumulative fatigue or variable amplitude loading can be obtained by the fatigue test. The fatigue machine of type HSM2*0*. was used for all fatigue tests. More details of this machine can be found in the machine test manual. Roberts et al. (2001)27. And illustrated in fig .(5)

Figure 5. Fatigue test machine

Values of alternating stress, σa, are obtained using the equation based on the modules of elasticity in bending (Eb)

$$\sigma_a = \frac{1.5E_b h\,\delta}{L_o^2} \tag{7}$$

where Eb is the bending modulus of elasticity, h is the thickness of sample, δ is the bending deflection, and Lo is the effective length which can be obtained by the formula

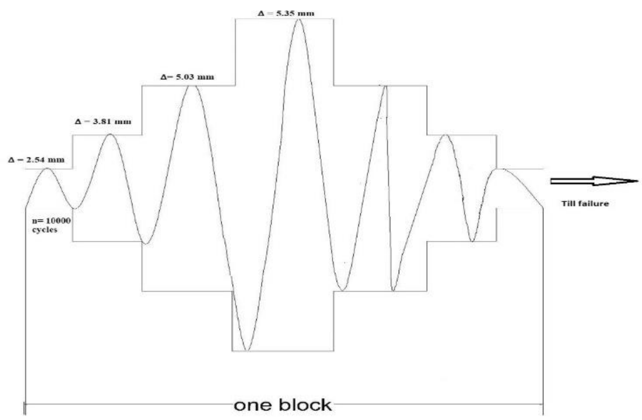
$$L_o = \frac{4L^2 - 2.465\delta}{4L} \tag{8}$$

where L is the half of the total specimen length or half the length between specimen holes or specimen holdings.

Cumulative fatigue (variable fatigue loading)

The model displays an inverse in deflection from a low value and for a number of applied cycles.as shown in Fig. (6) Then increasing by four valves of bending deflection. Then it gives up and repeats this program until the white area indicating failure appears as shown in Fig. 6.

Figure 6. Variable loading program



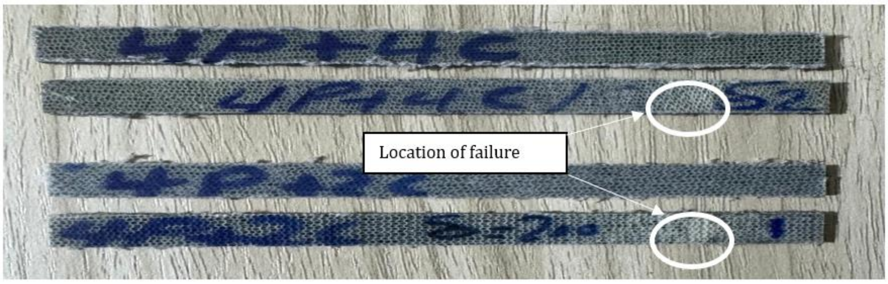
δ1< δ2 < δ3 < δ4

The high _ low fatigue test program can be subjected to the two composite materials used , starting from δ1=5.35mm, δ2=5.03mm, δ3=3.81mm and δ4=2.54mm till failure.

Failure definition

Fatigue failure is defined by the appearance of a clear white area across the width of the sample as shown in Fig. 7.

Figure 7. Failure definition



Results

Results based Tensile test

It was reported that the findings of the average of three samples of the materials (4P+2C) and (4P+4C) were captured. The stress-strain curve was determined by doing the tests at room temperature in order to get the best results. Table 2 presents the average findings for the two materials that were discussed before.

Table 2. Tensile results for (4P+2C) and (4P+4C)

UTS (MPa)	Et(GPa)	Material	Sample
31. 06	4.2	4P+2C	S1
53.114	6.6	4P+4C	S2

Bending test results

Table 3 shows the average of three bending samples tested under room temperature.

Table 3. Bending test results

Material	UTS (MPa)	Eb (Gpa)	Sample
4P+2C	194.126	6.2	S1
4p+4C	210.385	7.3	S2

The bending modulus of elasticity of the material used are 6.2 and 7.3 GPa for 2P+2C and 4P+4C respectively. These values will be used in order to calculate the value of alternating fatigue stress. Amer 28examined the same material but with different layer and he found the average bending modulus (Eb) of (8.25) GPa.

Constant amplitude Fatigue results (S-N)

When the structural members are frequently subjected to alternating loading over a long time at a level of stress substantially below the (UTS) ultimate tensile stress for nonrepetitive static loads, this phenomenon is called as fatigue. Frequently, an alternating stress (σa) that can be withstood for a specific number of cycles is called the fatigue strength of the material. The stress level that can withstood for an indefinite number of cycles is known as endurance fatigue limit (σE) of material. Fatigue data are frequently presented in the form of an S-N curve or stress – endurance curve.

Constant fatigue loading can be described by a constant alternating stress (σa) or alternating stress range (Δσ). All fatigue tests were done using stress ratio R = -1 fully reserved loading. S-N curve is stress-life curve which is a graphical representation of experimental fatigue results. In other words, the S-N curve represent the fatigue life in number of cycles at failure (Nf) and alternating constant amplitude of stress at failure (σa) (σf) The relation between (σf) and (Nf) can be formulated using Basquin formula as mentioned in equation (1)

Where A and α are material constants, can be obtained by equation (2) and (3)

The basic data for the laminations (4P+2C) and (4P+4C) can be illustrated in Table 4.

Table 4. Basic data for (4P+2C) and (4P+4C) laminations under constant fatigue amplitude

Lamination	Specimen thickness (mm)	Weight of specimen (gm)	Eb (GPa)
4P+2C	2	2.954	6.2
4P+4C	2.7	3.420	7.3

Four applied deflections or alternating stresses were subjected on four sample. For each deflection or stress level three specimens were examined. The deflection (δ) and alternating stress (σf) can be presented in Table 5. Note that the values of (Lo) was calculated using equation (8) while (σf) was obtained from equation (7).Table(5) give the deflection (δ) and stress at failure (σf)for (4P+2C) and (4P+4C) laminations respectively (1) and (6).

Table 5. Bending deflections (δ) and stress at failure (σf) for (4P+2C)

Deflection (δ) in (mm)	(σf) (MPa)	Lo (mm)
0.1 (2.54)	18.958	49.92
0.15 (3.81)	28.551	49.82
0.2 (5.08)	38.283	49.68
0.25 (5.35)	48.203	49.5

Table 6. Bending deflections (δ) and stress at failure (σf) for (4P+4C)

Deflection (δ) in (mm)	(σf) (MPa)	Lo (mm)
0.1 (2.54)	30.134	49.92

0.15 (3.81)	45.383	49.82
0.2 (5.08)	60.852	49.68
0.25 (5.35)	76.619	49.5

The experimental fatigue life (Nf) against stress at failure (σf) for (4P+4C) lamination can be presented in Table *7*.

Table 7. S-N curve results for (4p+2C) lamination

	σf (MPa)	Nf (cycles)	Nf (average)cycles
1,2,3	18.958	188720, 195000, 201280	195000
4,5,6	28.551	166260, 156820, 149600	157560
7,8,9	38.283	135689, 146127, 156678	146164
10,11,12	48.203	102680, 89688, 112870	101746

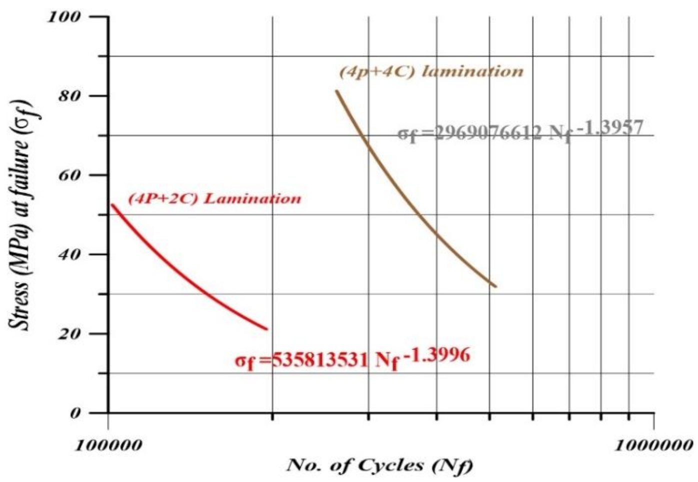
While the S-N curve results of the (4P+4C) lamination can be presented Table *8*.

Table 8. S-N curve for lamination (4P+4C)

	σf (MPa)	Nf (cycles)	Nf (average)
13,14,15	30.134	528600, 494300, 514234	512378
16,17,18	45.383	387462, 432667, 410699	410276
19,20,21	60.852	3726088, 317800, 328318	339602
22,23,24	76.619	235670, 281678, 269163	262172

The fatigue results of Table *7* and *8* can be plotted in Fig *8*.

Figure 8. S-N curves for laminations S1 and S2



The Basquin equations for the above laminations with R2 and endurance fatigue limit can be presented in Table 9

Table 9. S-N curves equations for 4P+2C and 4P+4C laminations

Lamination type	Basquin equation	R2	Endurance fatigue limit at 106 (Mpa)	h thickness (mm)
4P+2C (S1)	σf=535813531 Nf -1.3996	0.9762	2.145	2
4P+4C (S2)	σf = 2969076612 Nf-1.3957	0.9462	12.543	2.7

R2: coefficient of correlation

It is clear that (4P+4C) lamination has highly strength and life compared to (4P+2C) lamination. Sumeia and Al-Waily29 tested two composite lamination with 12 layers of perlon, woven carbon fibers , Kevlar and Kenaf and the other lamination without Kenaf. The thickness of samples was 3.8 and 4 mm for lamination without kenaf and with kenaf respectively. The test results showed that the strength and fatigue life's in comparison with the present work are illustrated in Table 10.

Table 10. Fatigue strength and life in comparison with Ref.29

	Composite material	σE (MPa)	Thickness	Fatigue life equation	Fatigue life at 60 (MPa) cycles
Present Work	4P+2C	2.145	2	σf=535813531 Nf -1.3996	60787
	4P+4C	12.543	2.7	σf = 2969076612 Nf-1.3957	325824
Ref. [29]	Lamination without kenaf	65.4	3.8	σf = 491.41 Nf -0.14	1797477
	Lamination with kenaf	90.89	4	σf = 673.84 Nf -0.14	13983500

Sumia and Al-Waily29 stuided the influence of kenaf fiber on the fatigue properties of below knee prosthesis composite material. They found that the fatigue strength was improved by 28% at 106 cycles and fatigue life was enhanced from 610 cycles without kenaf to 125204 cycles with kenaf at 120 MPa applied load and this showed 87.14% improvement percentage (IP). While the present work shows better fatigue strength and life for (4P+4C) composite material compared to (4P+2C) composite. The improvement percentage (IP) of the current study was 82.89% for fatigue strength at 106 cycles and 78.88% for fatigue life at 60 MPa applied load as shown in Table 11.

Table 11. Fatigue strength and life with (IP) for Ref. 29 compared to the current work

Ref. [29]				Present work			
Material	σEL at 106 (MPa)	IP (strength)	IP (life)	Material	σEL at 106 (MPa)	IP (strength)	IP (life)
4P+4G+4P	4.1495	64.27%	40.49%	4P+2C	2.145	82.89%	78.88%
4P+4C+4P	11.615			4P+4C	12.543		

Ehab et al [30] tested five groups of below prosthesis socket composite materials under constant and variable loads. The constant amplitude fatigue S-N curve equations in comparison with the present work can be listed in table 12.

Table 12 comparison between present work and Ref. [30]

Present work				Ref[30]			
Material	S-N curve equation	σE 106 Mpa	Nf cycles	Material	S-N curve equation	σE 106 Mpa	Nf cycles At failure
4P+2C	$\sigma_f = 535843531 N_f^{-1.3996}$	2.145	92542	4P+4G+4P	$\sigma_f = 1 \times 10^{12} N_f^{-1.897}$	4.1095	244584
				4P+4C+4P	$\sigma_f = 2 \times 10^{17} N_f^{-2.706}$	11.615	545088
				3P+2K+2P+2G+3P	$\sigma_f = 3 \times 10^{10} N_f^{-1.595}$	8.074	284380
4P+4C	$\sigma_f = 2969076612 N_f^{-1.387}$	12.543	352828	3P+2C+2P+2G+3P	$\sigma_f = 8 \times 10^{14} N_f^{-2.327}$	8.731	436800
				3P+2K+2P+2C+3P	$\sigma_f = 1 \times 10^{10} N_f^{-1.518}$	7.798	260758

Ehab30 found that the better composite for fabricating below knee prosthesis in strength and life was the composite (4P+4C+4P) and the less fatigue properties was (4P+4G+4P) composite.

The present results have taken the same trend compared to the result of Ref. 29 30.In the present experimental, the increase of two layer of carbon resulted in increase in the weight by 13.62% leading to improve in tensile, bending, endurance fatigue limit and fatigue life by 18.84%, 15.05%,82.89% and 78.88% respectively.

Variable fatigue loading results

This test was done by choosing increasing and decreasing program to know the effectiveness of variable loading on the fatigue life using Miner rule and new proposed model for this type of loading. The results are shown in Table13. Applications of Miner rule to the experimental results given in the Table 14.

Table 13. Fatigue results of (4P+2C) + (4P+4C) composites under variable Loading

4P+2C Low – high loading sequence				4P+4C Low – high loading sequence			
Test	Nf cycles	R repetition	D	Test	Nf	R	D

No.			damage	No.	cycles	repetition	damage
1	107622	1.537	0.43635	1	141800	2.025	0.2082
2	124008	1.771	0.50278	2	127668	1.823	0.1874
3	118746	1.696	0.48149	3	120718	1.724	0.1773
	Nf av 116792				Nf av 130062		
	4P+2C high – Low loading sequence				4P+4C high –Low loading sequence		
Test No.	Nf cycles	R repetition	D damage	Test No.	Nf cycles	R repetition	D damage
1	94680	1.352	0.6812	1	112620	1.608	0.3282
2	101600	1.4514	0.7313	2	108860	1.555	0.3173
3	106800	1.525	0.7684	3	102900	1.47	0.3000
	Nf av 101027				Nf av 108127		

Table 14. Comparison between the experimental variable fatigue life and Miner rule results.

4P+2C				4P+4C			
Experimental cycle		Miner cycle		Experimental cycle		Miner cycle	
L-H	H-L	L-H	H-L	L-H	H-L	L-H	H-L
116792	101027	124201	124201	130062	108127	375736	375736

It is obvious that the classical fatigue life predication, Miner rule apply for composite materials (4P+2C) and (4P+4C) which are used in prosthetic socket manufacturing is not satisfactory (overestimated the fatigue life). The reason is that Miner rule doesn't take into consideration of loading sequences effect. Ref 23 and it assumed that damage increase in linear manner while practically it propagates in nonlinear way Ref . 24

The proposed model

Equation (4) can describe the effect of loading sequences with the application of S-N curve equation. More details of this formula can be found in Ref.*26*

$$N_{fv} \; or \; N_{fc} = \frac{D\left(1-\frac{1}{\alpha}\right)(\sigma_H-\sigma_L)}{\left(\sigma_H^{1-\frac{1}{\alpha}}-\sigma_L^{1-\frac{1}{\alpha}}\right)A^{\frac{1}{\alpha}}} \quad (10)$$

In order to take in consideration most of the factor that effect the fatigue life of the composite material that the prosthetic socket manufactured. Damage in this work may be defined as:

$$D = \left[\frac{\sigma_H}{\sigma_L}\right]^{\alpha\frac{(UTS)tensile}{(UTS)bending}} \quad (11)$$

The result of application of the proposed model can be shown in Table *14* compared with the experimental and Miner prediction.

Table 15. Fatigue lifetime: predictions and experiment

Material	Nfv (exp.) cycle	Nfv (Miner) cycles	Nfv (proposed model)
4P+2C	116792	124201	105768
4P+4C	287667	357736	256125

Discussion

The fatigue lifetime of below knee prosthetics material under random loads depends on various parameters, including the consideration of design, the used material and the prosthetic intended used.

The results of the proposed model showed safe quests compared to the experimental results and Miner's estimation, and this is due to the following Ref. 24 31 The proposed model takes into account the effect of the sequence of stresses. The model includes S-N curve characters The model also includes tensile and bending mechanical properties. It is obvious from results in Table 12 that Miner's estimation is higher than the experimental and that is because Miner depends on the damage progress in a linear manner. Whereas in fact, the damage develops and increase in a non-linear fashion. So a model is suggested that depends on the non-linear relation and it includes many factors from which S-N curve properties as well as the tensile and bending properties. For these reasons the estimations of the proposed model were safe.

Conclusions

The composite materials that are utilized in the fabrication of the below knee prosthetic socket were subjected to a fatigue damage test that involved continually rising and decreasing stress amplitudes. We used two different composite materials: (4P+2C), which consisted of four layers of perlon and two layers of carbon, and (4P+4C). Both the tiredness sample and the exhaustion sample weighed 2.95 and 3.42 grams, respectively. For the purpose of utilizing some of these characteristics in fatigue analysis, tensile and bending tests were carried out. In the case of the two samples that were utilized, the values of the (UTS) and (UTS)B were 43.106 and 194.126 MPa for (4P+2C) and 53.114 and 210.385 MPa for (4P+4C) respectively. However, the modulus of elasticity in tensile and bending was measured to be 4.2 and 6.2 (GPa) for (4P+2C), and 6.6 and 7.3 (GPa) for (4P+4C) correspondingly. These values were recorded and recorded. Due to the fact that fatigue is thought to be the primary cause of socket failure, tests with constant and varied amplitudes were carried out on an experimental program that was continually growing and decreasing. The study that is being discussed in this article focuses on the durability and durability of two different types of laminated composites that were stated before.

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