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Mechanical Properties of Experimentally Calculated Carbon Fiber

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Abstract— Due to the expansion in the use of composite materials in various industries, also they are widely used in biomechanics, especially in the manufacture of prosthetics. Therefore, in this paper, four-layer carbon fiber material with lamination resin will be used to manufacture carbon fiber mold by experimental vacuum method, then the mold is cut with CNC machine to obtain the required samples for tensile test and fatigue test. Whereas, the tensile examination of the samples is to know the mechanical properties of the composite material such as Young's modulus, ultimate stress and yield stress, while the fatigue examination of the samples is to extract the relationship between the number of life cycles and stress, which is called the S-N curve. These properties and specifications are compared with previous research that used the same composite materials in the manufacture of samples. It was found that the results of this work have good specifications due to the accuracy in the casting process using completely vacuum, the care in paving carbon fibers and the use of materials of internationally approved origins that improved the mechanical properties of the samples. The mechanical properties were calculated and the Young's modulus = 20 GPa and the ultimate stress = 212 MPa. Also, an increase in the number of life cycles of applied stress was observed, as will be noted in the S-N curve, so composite materials (carbon fiber + lamination resin) can be used in the manufacture of prosthesis limbs, especially prosthesis feet because of their good properties and specifications.

Keywords— Composite material, Carbon fibers, Lamination resin, Casting, Molding, Mechanical properties.

1. Introduction

The main purpose of testing the samples that will be made experimentally from carbon fiber and lamination resin is to extract their mechanical properties and calculate the S-N curve values for the use of these composite materials mainly in the manufacture of prosthetic limbs, which is one of the most prominent applications and uses of biomedical engineering, which has witnessed great development and remarkable progress. This development has also led to the development of devices, medicines, surgical interventions and engineering materials in a remarkable way [4].

Over the previous decade, innovations and technology, as well as research and examination have significantly extended the usefulness and feel of prosthetic feet that were made of heavy steel and wood materials. Over the years old materials have been replaced by new materials such as metal alloys, lightweight plastics, and carbon fiber composites [1].

The best materials used in the manufacture of artificial limbs are polymer blend materials, especially in recent years, which have witnessed technological developments in this field through wide applications and uses. This new mixture has been used, which is self-treating and can be employed in the manufacture of prosthesis feet with acceptable mechanical properties and cost reasonable with increasing tensile strength of blends of this polymer by carbon fiber (CF) [7]. There are no accurate data and statistics worldwide for the number of amputees due to the lack of a comprehensive and unified database for all countries to help us collect and analyze this data, but it is estimated in the millions and this data may be collected in the future [15]. For example; there is a statistic for six countries in the world for the number of amputees, in which in which a high rate of amputees was noted due to the explosion of landmines. According to "Landmine Statistics, One World International, in London 2001" are given in **Table (1)** [8].

Table 1: Number of people amputated in six countries due to landmines.

State	No of amputee per all people	No of people	No of amputee
Angola	1 amputee per 334 people	10,145,267	30,375
Cambodia	1 amputee per 384 people	12,212,306	31,803
Afghanistan	1 amputee per 631 people	25,838,797	40,949
Iraq	**1 amputee per 987 people**	**22,675,617**	**22,974**
Vietnam	1 amputee per 1182 people	78,773,873	66,645
United state	1 amputee per 732 people	278,058,881	380,000

Many researchers have studied the use of the main materials that were used in the manufacture of prosthetics are iron, other metals, or wood, with parts made of leather that act as suspension systems. In view of the sudden and large increase in the number of amputees with the end of World War II, which required a wide and increasing interest in the improvement and development of prosthetic feet and with new materials [22]. For several centuries, the only materials used in the manufacture of prosthetics were wood and leather, but today prosthetics scientists have a much wider scope and range than before, now allowing the use of advanced plastics or carbon fibers, which are more durable, comfortable, tolerable, lighter and much stronger [14].

In 1960 AD, the two scientists, Le Petit Lorrain and Ambroise Paré [21], used new materials to be used in the manufacture of prostheses limbs, which are known as composite materials with low resistance. Subsequently, new composite materials were developed, using mainly carbon fibers and thermal resins, a significant development occurred in the design of prosthetics and orthotics. In 2000, Torst F. J. [20] examined different materials for their ability to store energy when used and compressed by body weight during the early standing stage, sufficient number of feet were provided for energy storage, it was found that most of the amputees responded that they exercised activities such as running, climbing stairs and jumping easier than storing energy with feet. At 2008, Nolan L. [17] has previously done a comprehensive review of the use of carbon fiber in the manufacture of prostheses limbs and studied its effect on the technique of running for amputees through the tibia, and reviewed the development and improvement of function and performance of carbon fiber for prostheses limbs during twenty-five years. While in 2013, Leonard Gabriel [16] studied layered composites of epoxy pre-reinforced blades reinforced with radial and unidirectional carbon fiber fabrics, and concentrated on the analysis of the thermal and mechanical behavior of these composites. These layered classifications are utilized to build prosthetic "J" blades to support prosthetics used by runners in the competition and training stages.

After this, at 2017, K. M. Walke and P. S. Pandure [13] studied the mechanical properties of various materials used in prosthetic feet, where they were compared to analyze the properties of the materials through assumed boundary conditions, and the materials that were studied are carbon fiber (CF), glass fiber(GF), carbon fiber reinforced (CFR) and Kevlar, where the mechanical properties of the materials are analyzed and calculated to meet the required values of toughness, flexibility, high tensile strength, higher shear strength, corrosion resistance, low density, in addition to the appropriate cost. After conducting several practical tests, they reached important results and conclusions, as it was found that the direction of the fibers has a direct effect on the mechanical properties. It was noted that mixing carbon fiber (CF) with silicone rubber (SR) and Poly-Methyl Metha Acrylate (PMMA) increases the bending strength by 17%, also when mixing carbon fiber (CF) with glass fiber (GF) increases the durability with improvement in mechanical properties in addition to reducing cost, also noted that mixing carbon fiber (CF) with Kevlar (hybrid mix) gave an excellent improvement in most of the mechanical properties. In general, the appropriate material is selected for the patient according to his weight, walking method, and the required activity. And Conor Sheehan and Elaine Figgins at 2017, [5] compared the mechanical properties using different percentages of carbon fibers used in one type for making the ankle foot orthosis (AFO), experimental and practical tests were conducted to find out the elastic properties, the obtained results showed that the stiffness is greater in the case of tension, the angular deflection is greater in the lite group and less than in the rigid group and that failure happens mainly at the fracture near of the strut. Also, in 2017, Hassanein Salih Hussain and Ayad Murad Takhakh [9] made a comparison between prosthetic feet - partial limbs - made of composite materials such as Perlon-Carbon–Perlon (PCP) or Hybrid Carbon Fiber with Glass Fiber (CF-GF) with Prosthetic feet made of traditional plastic materials such as Polypropylene (PP) or Polyethylene (PE), when carrying out the necessary tests to calculate the mechanical properties, it was clearly observed that the yield stress, the ultimate stress, Modulus Elasticity and maximum bending stress $(\sigma_y, \sigma_{ult}, E \text{ and } \sigma_b)$ increased significantly when using PCP compared with PP and PE, and more than when using CF-GF, therefore, when using these new composite materials, the prosthesis limb bears high loads, is much stronger, resists mechanical conditions, reduces elongation, and has a much longer life with reduced cost and periodic maintenance compared to limbs with traditional properties made of plastic. Finally, in 2020, Kelechi D. Kelechi et al. [12] showed that the tensile, extension, compression and flexion strength in addition to energy distribution when applying a load is determined by the quantity and quality of materials used in the manufacture of amputee prostheses, the repetition of this dynamic response, especially in the feet made of carbon fiber, appears clearly in addition to its appropriate cost. Their study showed when four different samples of dry rattan cane were used in the research, which were exposed to biomechanical testing and analysis that had good tensile and compressive strength enough to be used as a basic bioengineering material in the field of medicine.

In addition to other researchers, they manufactured samples of different composite materials and extracted specific results, but in this paper, a composite material consisting of carbon fibers with lamination resin was selected and the mold was manufactured experimentally, and from the mold samples that gave good results with high mechanical properties were obtained, then doing by comparing the results between them and the results of other researchers and discussing the results.

2. Analytical Investigation

The important main equations related to stress, strain, fatigue and others will be used, known laws such as Hooke's law and the derivation of the relationships required at work using the appropriate boundary conditions.

2.1 *The assumptions and approximations*

To facilitate the theoretical calculations and the application of the governing equations, some assumptions and approximations will be assumed to make the results more accurate and realistic, as follows:

1. It is assumed that the material used is isotropic and homogeneous.
2. Carbon fibers with lamination resin are distributed symmetrically in all regions of the molding, which means that it carries the same volume fraction for all regions.
3. When using the relationship stress and strain, assuming that the volume is constant.
4. Very small values, which represent the product of two or more strains of different axes, are neglected, as it will show in the subsequent derivations in this section and appendix.
5. The carbon fiber used, which is in the form of woven, is inclined at 45^0 angles for all layers.

2.2 *Equations and derivations*

The relationship between the changes in length to the original length is called the strain as in the following relationship:

$$\epsilon = \frac{L' - L}{L} = \frac{\delta\ (m)}{L(m)} \qquad (1)$$

Where $\epsilon, \delta, L,$ and L' are the strain (dimensionless), the change of length, the original length, and the final length of the member, respectively [2].

While the relation between the axial force (P) or load and the cross-sectional area (A) is called normal stress (σ) as:

$$\sigma\ (Pa) = \frac{P\ (N)}{A\ (m^2)} \qquad (2)$$

And the relation between the stress and the strain is called Young's modulus (E) according to Hooke's law:

$$E\ (Pa) = \frac{\sigma}{\epsilon} \qquad (3)$$

From the previous three equations, it is obtained:

$$\delta = \frac{PL}{AE} \qquad (4)$$

This equation has been experimentally proven [19].

In the state of using two dimensions (L and d) , when the sample is subjected to tension, an increase in length occurs, corresponding to a reduction in width (δd), the relationship between them is called Poisson's ratio (ν) [6]:

$$\nu = \frac{-\delta d/d}{\delta L/L} = \frac{-\epsilon_y}{\epsilon_x} \qquad (5)$$

$$G = \frac{E}{2(1+\nu)} \text{, where (G is Shear modulus)} \qquad (6)$$

By using the generalized Hooke's law for three dimensional state of stress which is suitable for homogeneous and isotropic materials as follows [2]:

$$\left.\begin{aligned} \epsilon_x &= \frac{1}{E}\left[\sigma_x - \nu\left(\sigma_y + \sigma_z\right)\right] \\ \epsilon_y &= \frac{1}{E}\left[\sigma_y - \nu\left(\sigma_x + \sigma_z\right)\right] \\ \epsilon_z &= \frac{1}{E}\left[\sigma_z - \nu\left(\sigma_x + \sigma_y\right)\right] \end{aligned}\right\} \qquad (7)$$

The previous equations are derived using the constanty volume property and neglecting the small terms that are of the second-order (e.g. $\epsilon_x\epsilon_y$) and the term of the third-order ($\epsilon_x\epsilon_y\ \epsilon_z$) which is relatively smaller, as the two equations below are deduced:

$$\sigma_x \cong \frac{E\epsilon_x}{1+\nu} \qquad (8)$$

$$\sigma_x \cong 2G\epsilon_x \qquad (9)$$

$$\because \sigma_b = \frac{My}{I} \qquad (10)$$

where $\sigma_b, M.y$ and $I$are the bending stress, the bending moment, the distance between the force and neutral axis, and the second moment of area, respectively [6].

And the distance between the force and neutral axis is [11]:

$$I = \frac{width \times (height)^3}{12} = \frac{bh^3}{12} \qquad (11)$$

The deflection for cantilever beam (Δ) as [18]:

$$\Delta = \frac{PL^3}{3EI} \quad \Rightarrow \quad \frac{P}{I} = \frac{3\Delta E}{L^3} \qquad (12)$$

From the equation (10) for calculating the bending stress (σ_b) of the cantilever beam:

$$\sigma_b = \frac{My}{I} \quad \Rightarrow \quad \sigma_b = \frac{P}{I} \times L \times {}^{t}/_{2} \qquad (13)$$

Where:

$$(M = P \times L), \text{ and } \left(y = {}^{t}/_{2}\right).$$

Substitute equation (12) in equation (13), get:

$$\sigma_b = \frac{3\Delta E}{L^3} \times L \times {}^{t}/_{2}$$

$$\therefore \sigma_b = 1.5 \times \frac{\Delta E t}{L^2} \qquad (14)$$

3. Experimental Work

3.1 *Preparing the selected material*

The molding is manufactured using the composite material consisting of carbon fiber cloth made in Germany by ottobock company, in the form of four layers with the use of a lamination resin type (80:20) material , it is considered a filling material that permeates between the layers of carbon fiber woven into its fibers at (45^0) angles.

3.2 *Sample casting and cutting*

To obtain the required samples, the following steps will be performed:

Step 1: The molding is cast using gypsum the surfaces in this molding are taken care of in terms of equatorially, smoothness and symmetry.

Step 2: A cover called Poly-Vinyl Acetate (PVA), is used to wrap the molding, and the process of vacuuming the air when packing, as in **Figure (1)**, the benefit of using PVA is as a separating and insulating material between the moldings made of gypsum and carbon fiber that has been paved over the molding.

Figure 1: The gypsum molding with PVA.

Step 3: The carbon fiber is paved with four layers over of the PVA material and from all sides, then the four layers of carbon fiber are also coated with the PVA material as in **Figure (2)**.

Figure 2: Carbon fiber layers.

Step 4: After adding the hardened powder to the lamination resin, it is poured from the top into the outer PVA, and the vacuum process is carried out, where the resin material permeates inside the carbon fibers and fills all the voids. After waiting for about (25 to 30) minutes until the vacuum process is completed and the carbon fibers are completely saturated with the resin, as in **Figure (3)**.

Figure 3: Carbon fiber with lamination resin.

Step 5: After the casting is completed, the mold is cut into two types of samples, one for tensile testing and the other for fatigue testing using the CNC machine, where the computer of the CNC machine is provided with shape and dimensions of the samples.

This machine gives an accuracy in dimensions of the required samples with the smooth edges finishes, as the molding is cutting with a drilling rig in a CNC machine at a high rotation speed of up to (18,000 rpm) with a slow linear movement to ensure accuracy in dimensions with smoothness in the internal surfaces.

The specifications of the samples are as follows:

1. The shape and dimensions of the samples for tensile testing shall be according to the international classification (ASTM D-638) as shown in **Figure (4)**.

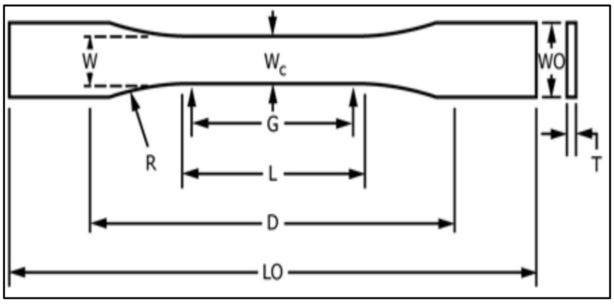

Figure 4: Tensile test sample.

Where: LO (Length overall, min) = 165 mm, T (Thickness of sample) = 2.2 ~ 2.4 mm, W (Width of narrow section) = 13 mm, WO (Width overall, min) = 19 mm, R (Radius of fillet) = 76 mm, G (Gage length) = 50 mm, L (Length of narrow section) = 57 mm, D (Distance between grips) = 115 mm.

2. The dimensions of the fatigue test samples as in **Figure (5)** shall be according to the specifications of the equipment used for the fatigue test.

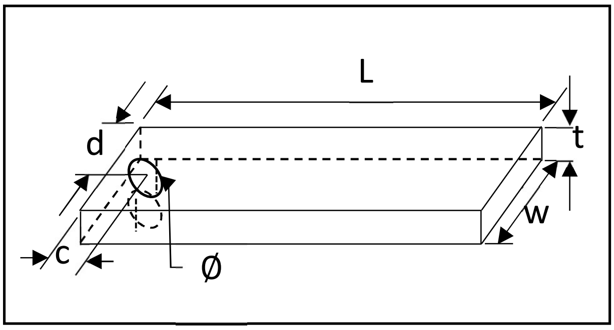

Figure 5: Fatigue test sample.

Where: L (Sample length) = 100 mm, w (Sample width) = 10 mm, t (Sample thickness) = 2.2 ~ 2.4 mm, Ø (Hole diameter) = 4 mm, c and d (The distance between the edge and the center of the hole) = 5 mm.

3.3 *Tensile test*

The samples required for tensile test as in step 5 in the previous paragraph were prepared using a tensile test device as in **Figure (6)** where 8 samples of thickness (t = 2.3~2.4 mm) will be tested.

Figure 6: Tensile test instrument.

Through the test with this instrument, the value of the maximum force and maximum elongation is obtained for the sample to reach the stage of failure or fracture, as shown in **Figure (7)** which shows the behavior of the composite material, and the values of the ultimate stress, maximum strain and Young's modulus are computed for each sample as in **Table (2)**, where (W = 13 mm and L = 57 mm).

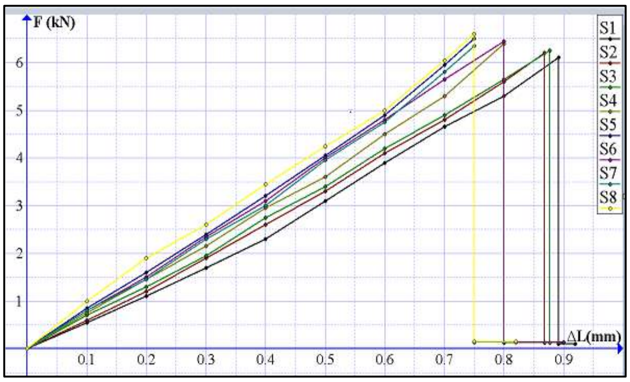

Figure 7: Force and elongation relationship for (8 samples).

Table 2: Results of the eight samples test.

No	Sample	*t (mm)*	*A (mm^2)*	From instrument		$\sigma_{ult}(MPa) = \frac{F_{max}}{A}$ Equation 2	$\epsilon_{max} = \frac{\Delta L_{max}}{L}$ Equation 1	$E(GPa) = \frac{\sigma_{ult}(1+\nu)}{\epsilon_{max}}$ Equation 8
				F_{max} *(KN)*	ΔL_{max} *(mm)*			
1	S1	2.2	28.6	6.1	0.892	213.287	0.01565	18.126
2	S2	2.25	29.25	6.2	0.868	211.966	0.01522	18.523
3	S3	2.3	29.9	6.25	0.877	209.03	0.01539	18.065
4	S4	2.3	29.9	6.4	0.8	214.047	0.01404	20.277
5	S5	2.35	30.55	6.5	0.75	212.766	0.01316	21.503
6	S6	2.35	30.55	6.45	0.8	211.129	0.01404	20.000
7	S7	2.4	31.2	6.35	0.7	203.526	0.01228	22.043
8	S8	2.4	31.2	6.6	0.75	211.538	0.01316	21.379
Average						210.911	0.014118	19.99

Figure (8) shows the shape of a number of samples after fracture that were tested in this instrument.

Figure 8: The samples after fracture.

From the results of the tests for the samples in the tensile test instruments, it was found that there is a clear convergence in the results, so the results shown below were relied on.

$\sigma_{ult.} \cong 211\ MPa$ and $E \cong 20GPa$

3.4 *Fatigue test*

The instrument shown in **Figure (9)** for the fatigue test will be used to calculate the values of the stress versus the number of life cycles curve (S-N curve).

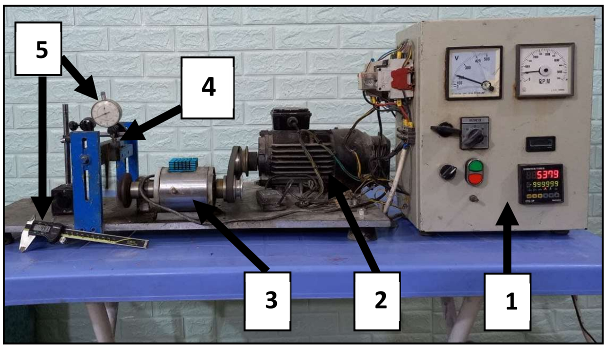

Figure 9: The fatigue test instrument for samples.

This instrument consists of the following main parts and accessories, and the indicator number of each part or accessory in the previous **Figure**:

1. The electrical board contains a tachometer, a voltmeter, a digital counter to calculate the number of cycles, in addition to a circuit breaker, electrical switches.
2. Electric motor with a power of (1 hp), a rotational speed of (3000 rpm) and a current of (1.9 A).
3. Transmission from the rotary movement of the electric motor to a linear movement up and down through its connection to the disc and the beam.
4. The sample to be tested.
5. The accessories are the dial gauge to accurately measure the required deflection when rotating, and the vernier is to measure the thickness of the samples and the effective length of the sample with high accuracy.

The samples were prepared as in the previous figure (5) with dimensions (length (L) = 10 cm, width (W) = 10 mm and thickness (t) ranged from (2.2 to 2.4 mm)), which are 24 samples.

The sample is attached to a cantilever support where the sample is on one side fixed and free on the other side linked to a vertical beam connected to a rotating disk that gives an upward and downward deflection during its rotation and this disk is connected to a rotating shaft joined to an electric motor as in **Figure (10)**.

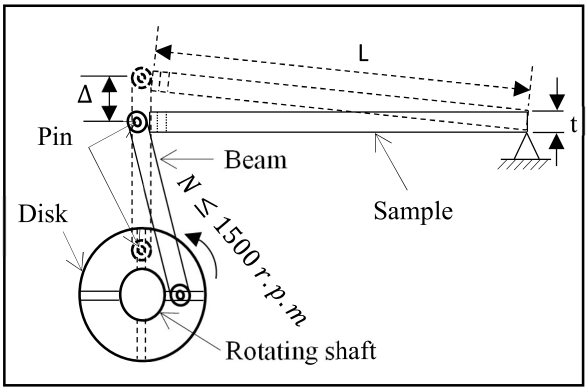

Figure 10: Schematic diagram of samples supported in fatigue tester.

From equation (14), get:

$$\sigma\ (MPa) = 3000 \times \frac{\Delta t}{L^2} \quad (15)$$

The samples will be tested as explained in the previous figure (5), with a number of (24) samples, with a thickness ranging from (2.2 ~ 2.4 mm), where the number of cycles is obtained until the sample fails as in **Table (3)**.

Table 3: Fatigue test results.

No.	S	t (mm)	L (mm)	Δ (mm)	$\sigma(MPa)$ Eq.(16)	N $(cycles)$
1	S1	2.4	30	26	208	10
2	S2	2.4	30	24.5	196	15
3	S3	2.3	31	26	186.681	25
4	S4	2.35	33	25	161.846	100
5	S5	2.4	34	25	155.709	125
6	S6	2.4	35	25	146.939	135
7	S7	2.35	35	24	138.122	400
8	S8	2.35	38	24	117.175	1000
9	S9	2.25	37	22	108.473	520
10	S10	2.35	40	24	105.75	3500
11	S11	2.35	40	23	101.344	4250
12	S12	2.3	40	22	90.563	10000
13	S13	2.35	45	25	87.037	20000
14	S14	2.3	47	25	78.09	30000
15	S15	2.4	50	25	72	100000
16	S16	2.35	50	23	64.86	200000
17	S17	2.25	51	24	62.284	250000
18	S18	2.4	55	25	59.504	350000
19	S19	2.3	52	23	58.691	500000
20	S20	2.25	50	21	56.7	600000
21	S21	2.2	50	20	52.8	1000000
22	S22	2.2	57	25	50.785	No fail
23	S23	2.25	60	25	46.875	although
24	S24	2.3	60	23	44.083	reaching more N> 3000000

4. Results and Discussion

The volume fraction (V.F) and the density (ρ) for samples are obtained, which are used in tensile test and fatigue test as shown:

1. The volume fraction is obtained, where the total volume (V_T) for mold which is made from carbon fiber and lamination resin is determined as:

$$V_T = 382.835\ cm^3.$$

The volume of lamination resin ($V_{lam.}$) used for casting of molding is:

$$V_{lim.} = 275\ mL = 275\ cm^3.$$

Therefore, the volume of carbon fiber ($V_{C.F}$) used for casting of molding is obtained as follows:

$$V_T = V_{C.F} + V_{lim.}$$

$$\Longrightarrow V_{C.F} = V_T - V_{lim.} \quad (16)$$

$$= 382.835 - 275$$

$$\therefore \quad V_{C.F} = 107.835\ cm^3$$

$$\because \quad V.F = \frac{V_{C.F}}{V_T} \quad (17)$$

$$= \frac{107.835}{382.835} = 0.2817$$

$$\therefore \quad V.F = 28.17\ \%.$$

2. To determine the density of samples the mass and volume of the selected sample must be known, since the dimensions of the selected sample were as shown:
   L (sample length) = 130 mm.
   w (sample width) = 60 mm.
   t (sample thickness) = 2.2 mm.
   The volume of sample $(V = L \times w \times t = 130 \times 60 \times 2.2)$
   $\therefore \quad V = 17160\ mm^3$

The mass of the selected sample was measured using an accurate digital balance where the mass was (m = 22.48 g)

$$\because \quad \rho = \frac{m}{V} \quad (18)$$

$$= \frac{22.48}{17160} = 0.00131\ {}^{g}/_{mm^3}$$

$$\therefore \quad \rho = 1310\ {}^{kg}/_{m^3}$$

The results for the manufactured samples, which include the tensile test and the fatigue test, will be calculated as follows:

4.1 *Tensile test results*

The tensile test values were calculated experimentally for the samples that were tested with the tensile device, according to the previous table (2).The relationship between the applied force (F) and the thickness of the sample (t) was drawn for eight samples as shown in **Figure (11)**:

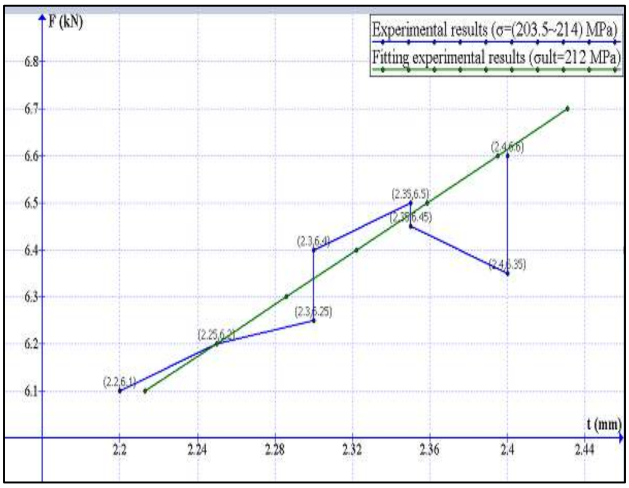

Figure 11: The force and thickness relationship for (8 samples).

From the above figure, it was noted that the values of the ultimate stress are variable for the samples, ranging from (203.5 to 214) MPa. The fitting line is made and using equation (2), ($\sigma\ (Pa) = \frac{F\ (N)}{A\ (m^2)}$) the value of the ultimate stress ($\sigma_{ult} \cong 212\ MPa$) is obtained.

The relationship between stress (σ) and strain (ϵ) was drawn for the same eight samples as shown in **Figure (12)**, it was noticed that the values of Young's modulus (E) are variable for the samples, ranging from (18.8 to 20.7) GPa. The fitting line is done to get the value of ($E \cong 20\ GPa$).

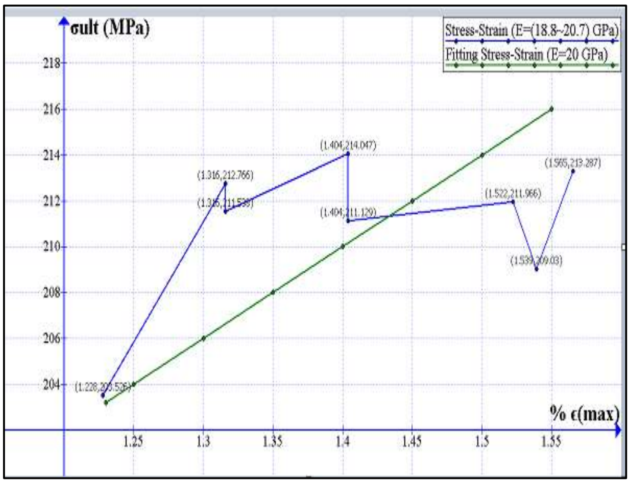

Figure 12: The stress-strain relationship for (8 samples).

Due to that, the strain is large compared to the stress so that the outcomes are not accurate in determining Young's modulus.

4.2 *Fatigue test results*

Through the fatigue test of the samples as shown in the previous table (3), where the result of sample (S9) will be neglected because it is not acceptable as it is far from the curve, as well as not entering the values of samples (S22, S23 and S24) because they did not fail the test although reaching more than $3*10^6$ cycles. The relationship between stress and the number of life cycles will be plotted, which is called S-N curve, the experimental results will be modified after approximating some results so that the fitting curve is more suitable with better accuracy as shown in **Figure (13)**.

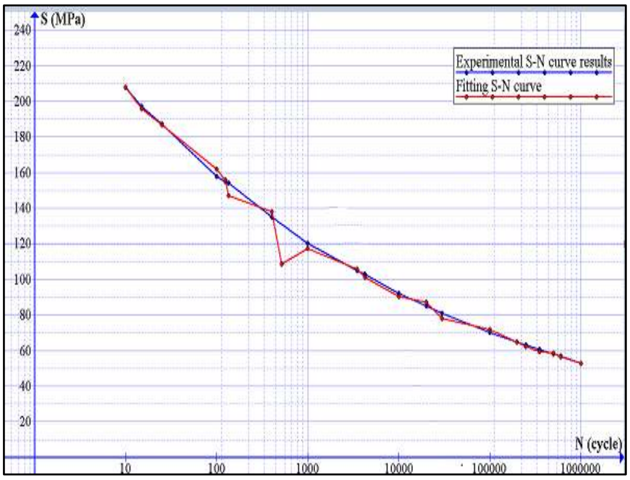

Figure 13: S-N curve.

These results are compared with two references [3] and [10], in which the same materials used in the manufacture of samples were used in this work with the same number of layers (4 layers) of carbon fiber with lamination resin, as shown in **Figure (14)**.

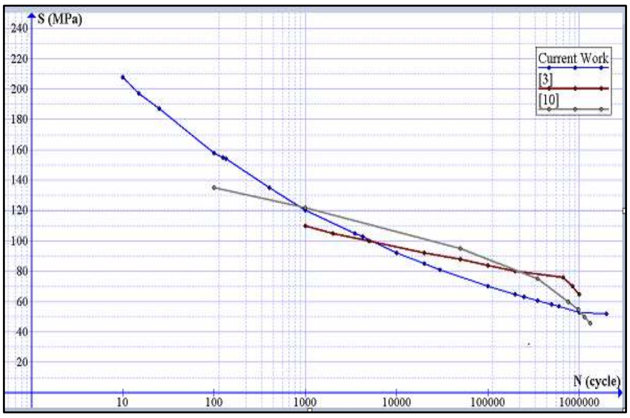

Figure 14: The comparison of S-N curves.

It was noted that the values of the results obtained experimentally in this paper are the results of testing samples with a larger number than required, as 24 samples were examined with variable stresses to obtain different life cycles, observance the accuracy of the examination when connecting the samples using the dial gauge and the precision digital vernier, as well as the accuracy in support and connect samples.

The relationship between stress and other variables (deflection, thickness and length) is drawn according to equation (15), ($\sigma\ (MPa) = 3000 \times \frac{\Delta \times t}{L^2}$) as shown in the following figures.

Figure (15) shows the relationship between stress and deflection is directly proportional assuming that the thickness (t = 2.3 mm) is constant and the relationship is plotted for different lengths (L_1 = 30, L_2 = 35, L_3 = 40, L_4 = 45 and L_5 = 50) mm.

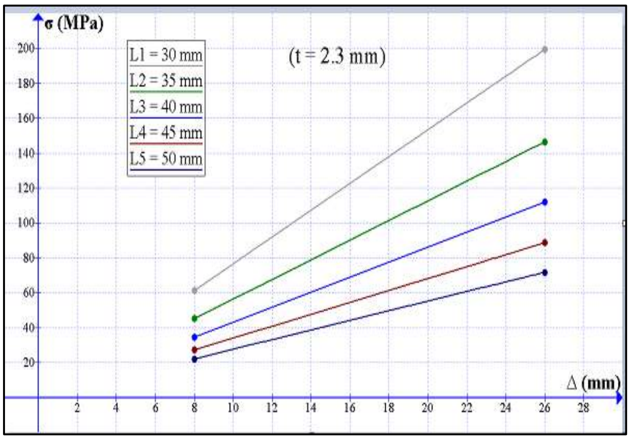

Figure 15: The stress / deflection relation.

Figure (16) shows the relationship between stress and thickness is directly proportional assuming that the deflection ($\Delta = 23\ mm$) is constant, the relationship is plotted for different lengths (L_1 = 30, L_2 = 35, L_3 = 40, L_4 = 45 and L_5 = 50) mm.

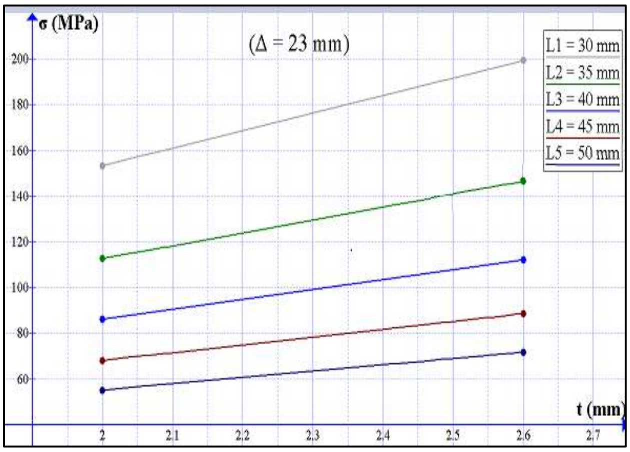

Figure 16: The stress / thickness relation.

Figure (17) shows that the stress is inversely proportional to the square of the effective length, assuming that the thickness (t = 2.2 mm) is constant and the relationship is plotted for different deflections ($\Delta_1 = 20, \Delta_2 = 23\ and\ \Delta_3 = 26$) mm.

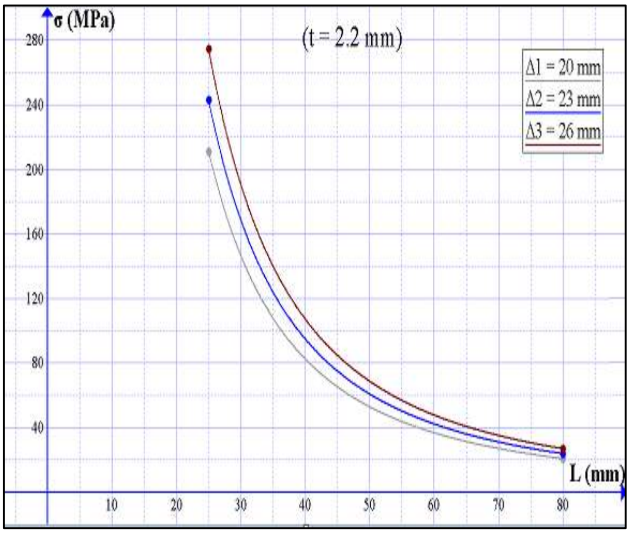

Figure 17: The stress / effective length relation.

When checking the drawing in the previous figure, it is noted that the effective length of the sample should be no less than (30 mm) because the stress increases significantly when (L < 30 mm) due to the generation of other stresses on the sample in addition to the bending stress, which was taken into account when examining the samples experimentally.

4.3 *Reasons of the difference in results*

The most important reasons for the difference between the experimental results can be mentioned as follows:

4.3.1 *Irregular casting of samples*

The most important reasons for the discrepancy and irregularity in the casting of samples and foot can be mentioned as follows:

1. At the stage of using the vacuum device when pouring samples, the thickness of the mold cannot be adjusted very accurately, as a small difference in the thickness of the samples cannot be distinguished by the macroscopic, but by using accurate measuring devices.
2. When cutting samples with a CNC machine, the ends and edges will be stiffer than other regions in the sample.
3. Internal gaps may occur in some samples during casting that cannot be seen with the macroscopic.
4. There is some difference in the volume fraction in the mold and foot regions.
5. It has been assumed that the samples are isotropic and homogeneous, which is an ideal condition that cannot be exactly achieved in practice.

4.3.2 *Variation in tensile test device for samples*

The reasons of the difference in results when using a tensile testing device for samples are:

1. When a sample failure occurs in only one area, it is shortened and then quickly interrupted, so the

failure is the weakest point in the sample and not in the whole sample.
2. Failure may occur in the sample before reaching the ultimate stress because the sample is made of a composite material, where the failure occurs in the resin before the carbon fibers, so the values of strain, ultimate stress and Young's modulus are approximate.

4.3.3 *Variation in fatigue test device for samples*

The main reasons of the difference in results when using the fatigue test device for samples are explained as follows:

1. The samples, after being connected in the fatigue test device, are subjected to rapid cycles of about (1500 rpm), which is a high speed compared to normal use, which generates heat in the samples due to the rapid movement of particles and not allowing them to return to their normal position, this heat may affect the sample and fail before the real failure.
2. The failure that occurs in the sample is observed through the macroscopic, but in fact, a microscopic internal crack or notch may occur that cannot be seen and diagnosed with the macroscopic, so it does not represent the real failure.
3. The instrument connections attached to the sample there are clearances in the beam, pin and disc that affect the accuracy of the effective length and deflection readings.
4. The alignment of the sample with the vertical beam should be at an angle of (90^0), which is manually adjusted.
5. The speedometer in the device is to measure the speed of the electric motor, while the transmission speed will be greater, in testing samples made of composite materials, the rotating speed of the disc must not exceed (1500 rpm) and this has been taken into account in practice.

5. Conclusions

The most important conclusions obtained in this work can be summarized, as shown below:

1. The error percentages are a kind of normal difference in the calculated results in the experimental work, where the error percentage in the results did not exceed (7.45%). In general, the reported error percentages are acceptable and within the natural variation for many reasons that were mentioned in the section on the reasons for the difference in results.
2. The mechanical properties obtained from the experimental results are good, high and have the ability to withstand great stresses and forces.
3. This composite material (carbon fiber with lamination resin) is used in the manufacture of dynamic prosthetic feet due to its good specifications and acceptable flexibility.

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الخواص الميكانيكية لألياف الكربون المحسوبة تجريبياً

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الخلاصة – نظرًا للتوسع في استخدام المواد المركبة في مختلف الصناعات ، فهي تستخدم أيضًا على نطاق واسع في الميكانيكا الحيوية ، وخاصة في تصنيع الأطراف الاصطناعية. لذلك ، في هذه الورقة ، سيتم استخدام مادة ألياف الكربون المكونة من أربع طبقات مع راتينج التصفيح لتصنيع قالب من ألياف الكربون بطريقة تفريغ الهواء تجريبيا ، ثم يتم قطع القالب بآلة CNC للحصول على العينات المطلوبة لاختبار الشد واختبار الكلال. حيث أن فحص الشد للعينات هو لمعرفة الخواص الميكانيكية للمادة المركبة مثل معامل يونغ ، وإجهاد الذروة ، وإجهاد الخضوع، في حين أن فحص الكلال للعينات هو لاستخراج العلاقة بين عدد دورات الحياة والإجهاد ، وهو ما يسمى منحنى S-N. تمت مقارنة هذه الخصائص والمواصفات مع الأبحاث السابقة التي استخدمت نفس المواد المركبة في تصنيع العينات، وقد وجد أن نتائج هذا العمل لها مواصفات جيدة نظرا للدقة في عملية الصب باستخدام تفريغ الهواء بالكامل والعناية برصف ألياف الكربون واستخدام مواد ذات مناشئ معتمدة دوليا أدت إلى تحسين الخواص الميكانيكية للعينات. تم حساب الخواص الميكانيكية ومعامل يونغ = 20 جيجا باسكال وإجهاد الذروة = 212 ميجا باسكال. كما لوحظ زيادة في عدد دورات الحياة للإجهاد المسلط ، كما يُلاحظ في منحنى S-N ، لذلك يمكن استخدام المواد المركبة (ألياف الكربون + راتنج التصفيح) في تصنيع الأطراف الاصطناعية ، وخاصة القدم الاصطناعية بسبب خصائصها ومواصفاتها الجيدة.

الكلمات الرئيسية – المواد المركبة ، ألياف الكربون، راتينج التصفيح، الصب ، القالب ، الخواص الميكانيكية.