Tensile and Fatigue Characteristics of Lower-Limb Prosthetic Socket Made from Composite Materials

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Abstract

In this work, five laminated composite materials used for manufacturing lower-limb prosthetic sockets were fabricated using vacuum molding technique. The matrix material of these composites wass Epoxy, reinforced with five types of woven fibers and particles: (perlon, glass, carbon, hybrid (carbon and glass) and hybrid (carbon and glass) with micro & nano Silica particles. The tensile and fatigue properties were measured experimentally. The theoretical part of this work deals with calculations of the fatigue ratio and theoretical factor of safety. The finite element technique (ANSYS-11) is used to analyze and evaluate fatigue characteristics. This was done by constructing five models for the socket which were treated as three-dimensional structure composite materials. The results show that changing the type of reinforcement has a great influence on the measured properties. (Epoxy + Carbon reinforcement) composites gave optimum experimental, numerical and theoretical results which make them the best candidate to improve the fatigue characteristics of trans-tibial prosthetic socket.

Keywords
Prosthetic, Trans-tibial, Fatigue, Ansys, Laminated composites.

1. Introduction
Prosthesis an artificial device used to replace a missing body part, such as a limb, tooth, eye, or heart valve. For optimal prosthetic performances, the socket must be facilitate motion. Forces, generated by the residual limb through gait motion, must be efficiently transmitted from the limb to the prosthesis; thus, any relative motion exhibited between the residual limb and the socket will challenge successful ambulation, thereby increasing fatigue and discomfort. Patients except to receive prosthesis with proper fit, ultimate comfort and functionality. Additionally, the prosthesis must be light weight and cosmetically appealing. Majority of the failure of prosthetic components are fatigue related under cyclic walking loads. Materials and mechanical properties of the prosthetic socket were studied by many investigators. T.A. Current et.al. quantified the structural strength of various trans-tibial composite sockets. Five different reinforcement materials and two resin type were used to construct the sockets [1]. A. A. Ibrahim investigate the structural strength of the syme prosthesis by proposing two laminate with different reinforcement materials [2]. Sam L. Philips and William Crelius initiates a data base on material properties of typical laminations used in prosthetic limb sockets, the authors subjected samples of common prosthetic laminations to tensile and bending tests. Eight varieties of lay-up materials (fibers) were each laminated separately with one of three common resins (matrix), resulting in 24 combinations of fiber/resin laminates [3]. H. F. Neama, presents analyses for below knee prosthetic socket. Socket stress distribution is performed on three types of sockets, polypropylene (5mm), polypropylene (3mm) and standard laminate (8 layers of nylglass) (3mm) sockets to determine the stress path through the prosthetic socket during gait cycle [4]. S. H. Mohammed investigated the ankle-foot orthoses numerically and experimentally using perlon-carbon-fibers-acrylic materials instead of typical used polypropylene materials [5]. This article reports the effect of materials type on the tensile properties (Young's modulus, tensile strength and elongation at break) and fatigue properties (S-N curve, strain energy-N and fatigue limit) of trans-tibial prosthetic socket, by quantifying socket's structural strength (Experimentally, Numerically and Theoretically) of five different reinforcement [perlon fibers, carbon fibers, glass fibers, (carbon + glass) fibers and (carbon + glass) fibers+SiO_2 particles] with Epoxy matrix.

2. Theoretical Part
Theoretical part of this article is based on the following Theories and Criteria:

Goodman relationship
Empirical relationships have been devised to describe the relationship between fatigue limit and mean stress [6]:

$$\frac{\sigma_a}{\sigma_e} + \frac{\sigma_m}{\sigma_{ts}} = 1 \text{ ....}(1)$$

Where:
σ_a = stress amplitude or Von Mises equivalent stress.
σ_e = stress at fatigue limit (endurance limit).
σ_m =mean stress.
σ_{ts} =Ultimate Tensile Strength.

Strain Energy criterion
The strain energy may be used as a fatigue failure criterion for fiber-reinforced materials. Since this parameter does not rely on the different failure modes obtained in composites, it gives equally good results independent of the failure mechanism [7]. The area under the stress-strain graph is the strain energy per unit volume as shown in the following equation [8]:

$$\Delta W = \frac{1}{2}\,\sigma\epsilon \ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Where:
ΔW = Strain energy (Joul/mm^3).
σ = stress value (MPa).
ϵ = strain value (%).

Von Mises Equivelent stress
The Von Mises stresses "allow the most complicated stress situation to be represented by a single quantity" [6] and can be calculated by the following equation[9]:

$$\sigma_{eq} = \left[\frac{1}{2}\left[\begin{matrix}(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2\\ +6(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)\end{matrix}\right]\right]^{\frac{1}{2}} \ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Where:
σ_{eq} = Von Mises equivalent stress
σ_x = principal normal stress in x-direction.
σ_y = principal normal stress in y-direction.
σ_z = principal normal stress in z-direction.
τ_{xy} = shear stress in xy-plane.
τ_{yz} = shear stress in yz-plane.
τ_{zx} = shear stress in zx-plane.

Maximum Shear Stress
The mathematical representation of maximum shear stress τ_{max} [6] , is:

$$\tau_{max} = \frac{\sigma x-\sigma z}{2} \ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

Factor of Safety
The maximum equivalent stress failure theory states that a particular combination of principal stresses causes failure if the maximum equivalent stress (σ_e) in a structure equals or exceeds a specific stress limit (σ_{ts}). Therefor the equation of safety factor can be written according to Goodman as follows [10]:

$$\frac{Sa}{Se}+\frac{Sm}{Su}=\frac{1}{SF} \ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

Fatigue Ratio (R_f)
The fatigue ratio (R_f) is the ratio of the endurance limit to the tensile stress [11] :

$$Fatigue\ Ratio\ (R_f) = \frac{Endurance\ limit(\sigma_e)}{Tensile\ Strength(\sigma_{ts})} \ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

3. Experimental Part

Materials used in below knee socket lamination
Materials needed in the lamination of the below knee socket for this study are: Epoxy resin, Carbon fiber stockinet, Fiber glass stockinet, Hybrid (Fiber glass + carbon) stockinet, Perlon stockinet and Nano and micro precipitated Silica particles with median particle size of (15µm). Other materials needed for the manufacturing of prosthetic socket were: Hardening powder, Polyvinyl alcohol PVA bag and Materials for Japson mold. The following tests were performed:

Tensile Test
This test is performed according to (ASTM D638) at room temperature with (5 KN) applied load and strain rate of (1 mm/min). Figure 1 shows a tension standard specimen [12].

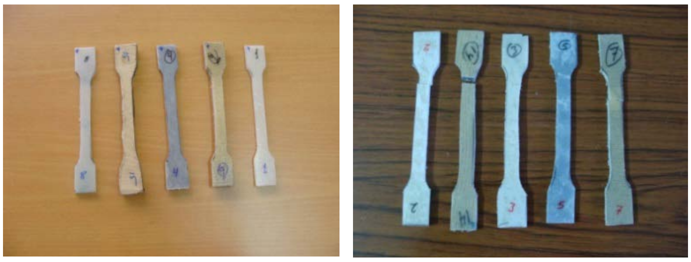


Figure 1: Tensile experimental specimens before and after test

Fatigue Test
The Fatigue testing used was by an alternating-bending fatigue testing machine with the specification of (fatigue testing machine HSM20, 1400 rpm ,spanning voltage 230 V , frequency 20Hz, Normal power 0.4 Kw), and performed at room temperature and a stress ratio of R= - 1 (tension– compression). Figure 2 shows the fatigue standard specimen test according to the machine's manual [13].

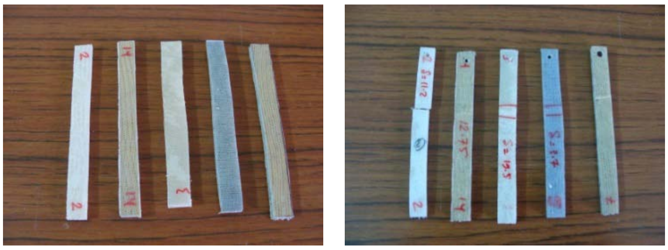
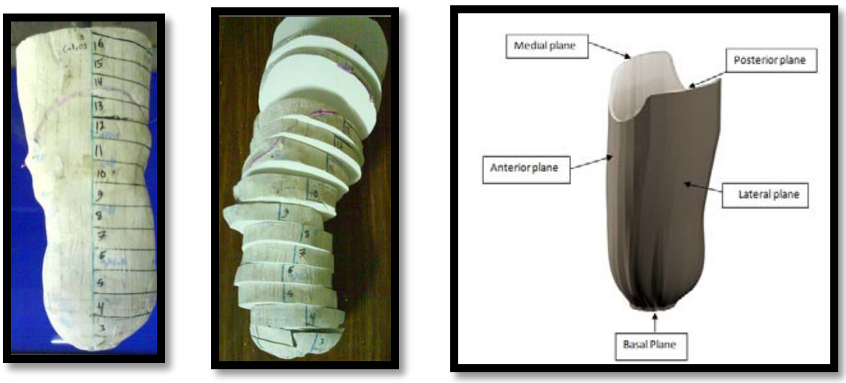


Figure 2: Fatigue experimental specimens before and after test

Finite Element Analysis (FEM)
Finite Element Analysis provides (Fatigue Life, Fatigue Factor of Safety, Equivalent Alternating Stress (Von Mises Stresses), Maximum total Deformation, Maximum Shear Stress) distribution of the simulated prosthetic socket of 75.5 kg in body mass. As shown in Figure 3. The socket is analyzed at the most extreme load conditions, which exist at heel strike in Gait cycle. Pressures values listed in table (1) were applied on sockets plane shown in Figure 3(c) [14]. The Ansys (11) package is used here for this type of analysis, the three-dimensional element is SOLID 185 as in Figure 4 is used for 3-D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. Figure 5 represents the mesh generation of the composite sockets.



a b c

Figure 3: a-Positive mold of prosthetic socket. b- Discs of positive mold. c-Auto CAD model of prosthetic socket

Table 1: Location and average pressure values of Heal strike generated in socket [15]

Location	Anterior	posterior	medial	lateral	basal
Average Pressure value (MPa)	0.011655	0.0444075	0.03434	0.045765	0.288

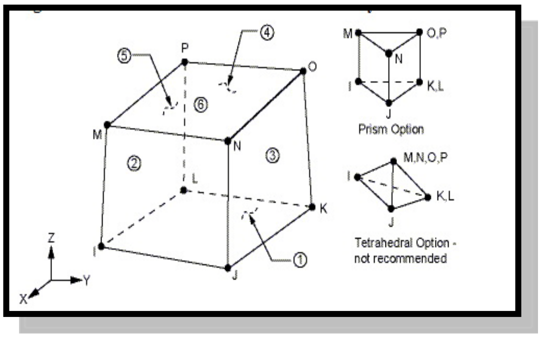


Figure 4: 3-Dim. element solid 185

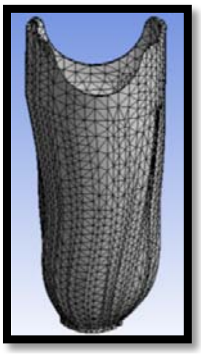


Figure 5: The meshed socket

4. Results and Discussion

Tension Test Results

This study compares the tensile properties (Young's modulus (E), Ultimate tensile strength, and percentage of elongation at break) of trans-tibial composite prosthetic sockets. Changing the type of reinforcement and matrix has a great influence on tensile properties. Tensile properties are shown in Figure 6. It can be seen from this figure that reinforcing with Carbon gives the optimum mechanical properties. Also adding SiO_2 particles to Hybrid (Glass+Carbon) reinforcement increase the tensile modulus and tensile strength significantly by 1.5 and 1.7 time respectively when comparing with Hybrid (Glass+Carbon) reinforcement alone and vice versa for elongation, because of the ability of Epoxy to bond perfectly to a wide variety of fibers [15] and the presence of SiO_2 particles hinderes the propagation of crack [16]. Also it is noted that reinforcement of Perlon gave the lowest tensile properties, meaning that perlon did not improve the properties of matrix material to any extent and the tensile properties of matrix are predominated in the overall behavior of the composites.

Fatigue Test / Stress-No. of Cycles(S-N) Results

The results of all fatigue tests carried out at various reinforcements are graphically displayed in the form of S-N curves shown in Figure 7. These curves are obtained by curve fitting the experimental data of fatigue test, using logarithmic formula [17]. The log equations which express the fatigue behavior of the composite are given in table (2). The fatigue limit (strength) of the tested materials is taken at No. of Cycle of 10^6. Since, beyond that No. of Cycles fatigue life becomes infinite [18]. In general, the fatigue limit of materials is proportional to its tensile strength [16]; hence materials with higher ultimate tensile strength possess higher fatigue limit. It is evident from Figure 7 that for all classes of laminates, reinforcement type have a pronounced influence on their fatigue resistance as shown in Figures 7 and 8 Carbon reinforcement gave the highest fatigue limit due to the high Young's modulus (E) and Ultimate tensile strength. Hybrid (Glass + Carbon)+ SiO_2 particles gave the second highest fatigue limit where the presence of SiO_2 particles increases the Young's modulus (E) and ultimate tensile strength of the material by hindering the propagation of crack [16] together with the high bonding of Epoxy with the reinforcement. It is illustrated from this figure that fatigue limit of Carbon reinforcement increases as much as eight times of magnitude as compared to Perlon reinforcement.

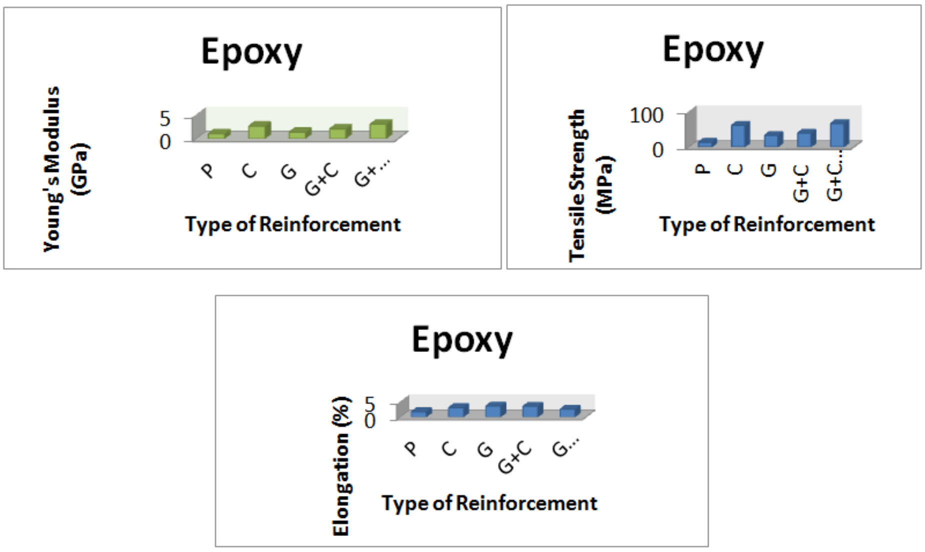


Figure 6: Tensile properties (Young's modulus, tensile strength, elongation (%)) of Epoxy matrix composites with various reinforcement

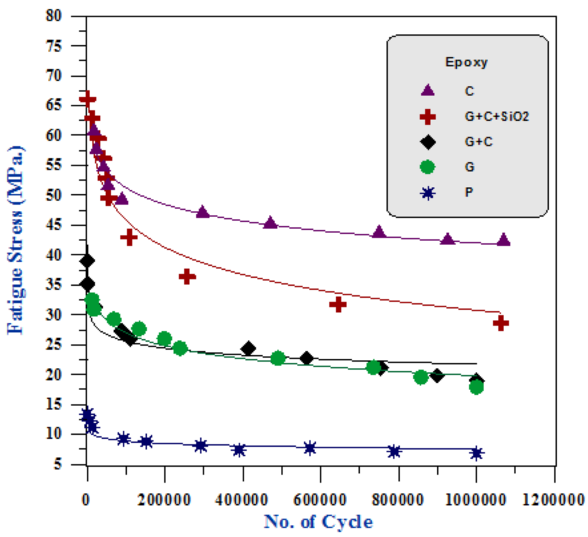


Figure 7: S-N curves of Epoxy matrix composites with various reinforcement

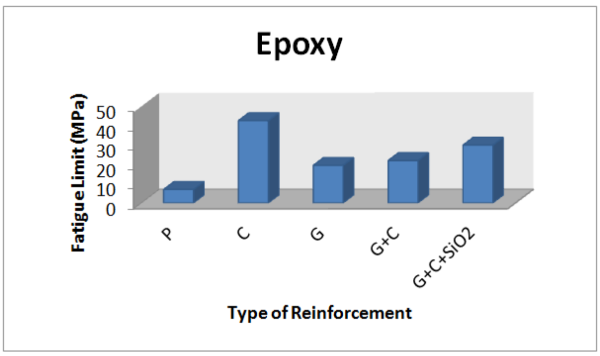


Figure 8: Fatigue limit of Epoxy matrix composite with various reinforcement

Fatigue Test / Strain Energy-No. of Cycles Results

Both stress and strain were recorded from tension test and used to evaluate strain energy and strain energy limit for the composites and plotted in Figures 9 and 10, respectively. It can be seen that (Epoxy + Carbon reinforcement) composite have the highest strain energy with 48.61 Joul/mm^3, that is logical since their stress and strain values are high which means that this composite material have the ability to store a large amount of energy before damage and failure take place. Also It can be seen that the perlon reinforcement gave the lowest values of Strain Energy and Strain Energy limits among all composites with 2.64 Joul/mm^3. This behavior comes from the low tension properties of this type of reinforcement. Also the logarithmic formula used in curve fitting the data of strain energy of Figure 9 as represented in Table 2.

Table 2: The Log equations of stress-N and strain energy-N curves

Matrix	Reinforcement	Curve fitting equation of Stress	Curve fitting equation of Strain energy
Epoxy	Glass+Carbon+SiO_2	σ = -6.54085 * log(N) + 121.118	ΔW = -11.9508 * log(N) + 177.242
	Glass+Carbon	σ = -1.66488 * log(N) + 44.7291	ΔW = -4.78709 * log(N) + 80.7927
	Glass	σ = -3.1103 * log(N) + 62.7729	ΔW = -8.94677 * log(N) + 136.583
	Carbon	σ = -4.01657 * log(N) + 97.502	ΔW = -10.7255 * log(N) + 184.472
	Perlon	σ = -0.574127 * log(N) + 15.479	ΔW = -0.785535 * log(N) + 14.0122

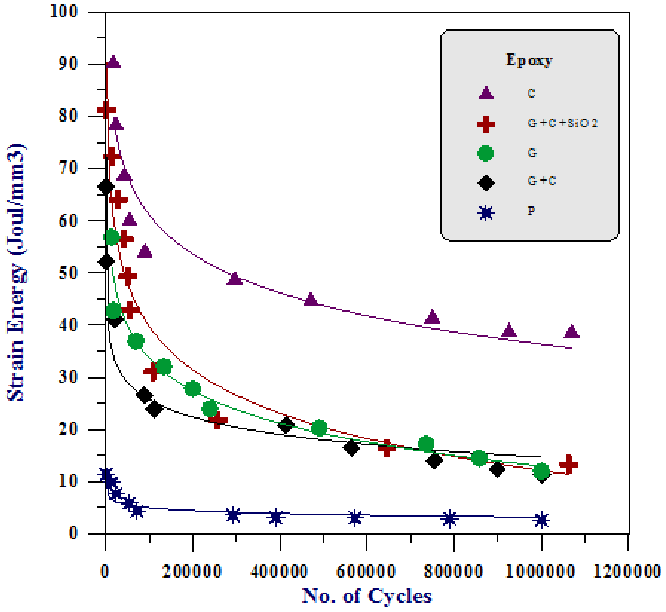


Figure 9: Strain energy - No. of cycles curves of Epoxy matrix composites with various reinforcement.

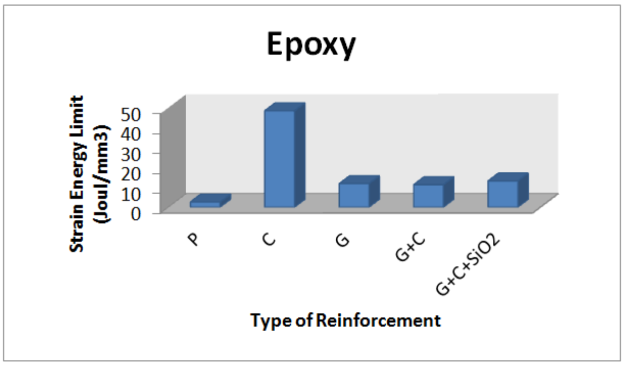


Figure 10: Strain energy limit of Epoxy matrix composites with various reinforcement

5. Numerical Results

Fatigue Life Results

Fatigue Life shows the available life for a given fatigue analysis. Counter plots shown in Figure 11 were used to display the overall distribution of life throughout the socket for each type of composite used in this study. In stress life analysis with constant amplitude, if the equivalent alternating stress is lower than the lowest alternating stress defined in the S-N curve, the life at that point will be used [6].

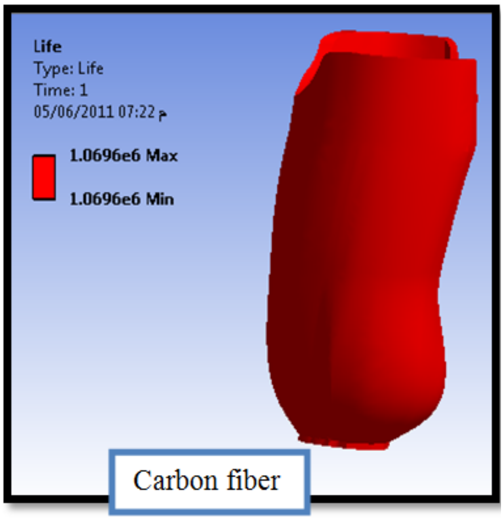


Figure 11: Sample of contours of fatigue life distribution

Fatigue factor of Safety Results

These are counter plots with respect to fatigue failure at a given design life. In Ansys, Maximum factor of safety displayed is 15, values less than one indicates failure before the design life has been reached [6]. It can be noticed in Figure 12 the distribution of safe and unsafe regions of the composites. Minimum safety factor of each composite is recorded in the mentioned figures above where it can be seen that (Epoxy + Carbon reinforcement) composite had the highest safety factors of (6.9581) It is obvious that all materials are safe.

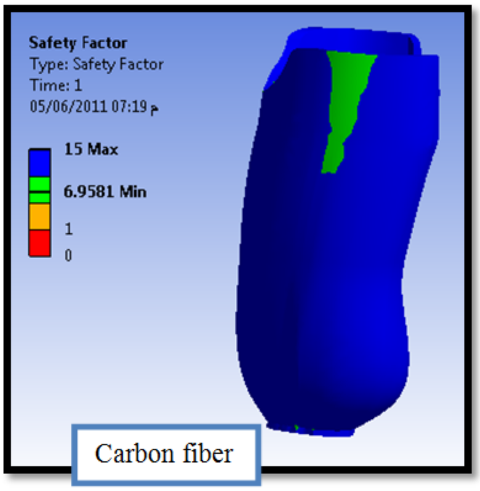


Figure 12: Sample of Contours of Fatigue Safety Factor distribution

Equivalent alternating stress (Von Mises stresses) Results

Equivalent alternating stress is the stress used to query the fatigue S-N curve after accounting for fatigue loading type, R-ratio effects and any other factors in fatigue analysis. Equivalent alternating stress is the last calculated quantity before determining the fatigue life [6]. Figure 13 shows contour plots of the Epoxy composites which display the overall distribution of the Von Mises stresses throughout the material, as well as to determine the approximate location and value of the maximum Von Mises stresses. It can be seen from these figures that the highest values of Von Mises stress is concentrated in the lateral and basal planes of socket.

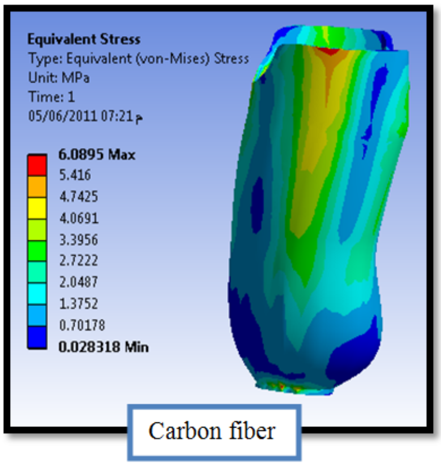


Figure 13: Sample of Contours of Equivalent Von Mises stress distribution

Fatigue Total Deformation Results

Figure 14 shows the total deformation for Epoxy composite. The highest total deformation values can be seen in Perlon reinforcement. The lowest amount of total deformation can be seen in Epoxy with Hybrid (Glass + Carbon)+ SiO_2 particles composite with (1.467) mm. It can be seen from these figures that the highest values of total deformation is concentrated in the lateral plane of socket and the smallest values of total deformation is concentrated in the basal plane of socket.

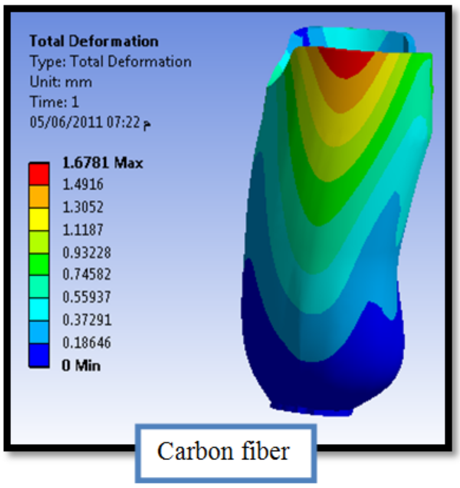


Figure 14: Sample of total deformation

Maximum Shear Stress Results

Figure 15 shows contour plots of the composites which display the overall distribution of the Maximum Shear Stress throughout the material, as well as determine the approximate location and value of the Maximum Shear Stress. It can be seen from these figures that the highest values of Max. Shear Stress is concentrated in the lateral and basal planes of socket.

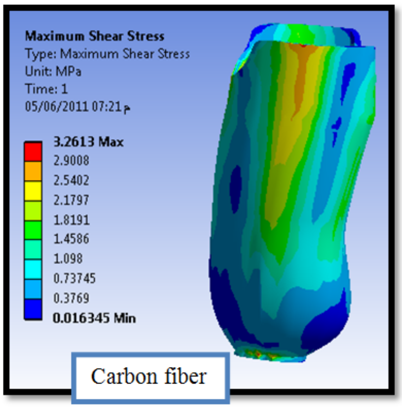


Figure 15: Sample of Max. Shear Stress

6. Theoretical Results

Fatigue Ratio (R_f)

Figure 16 shows the relationship between fatigue ratio and type of reinforcement, it can be seen from this figure that fatigue ratio of (Epoxy + Carbon reinforcement) composite was the highest with 0.7. Since, both Fatigue Limit and Tensile strength of these composites are the highest between the other composites which coincide with the experimental result.

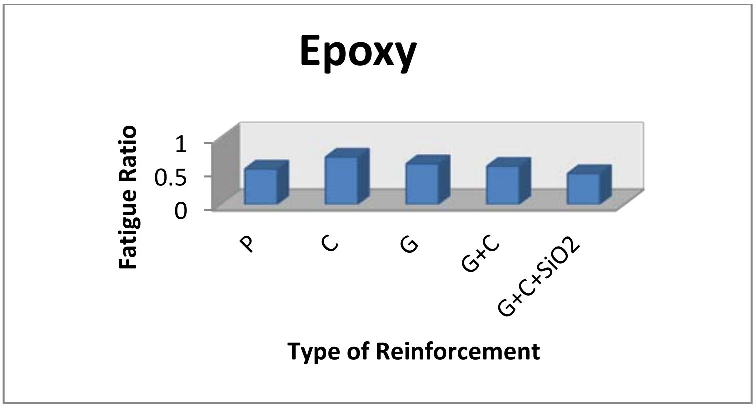


Figure 16: Fatigue ratio of Epoxy matrix composites with various reinforcement

Factor of Safety (SF)

Safety Factor of the composite materials is obtained according to Goodman theory [10]. Figure 17 shows the relationship between factor of safety and type of reinforcement used in this study, it can be seen from this figure that the factor of safety of (Epoxy + Carbon reinforcement) composite give the highest Safety Factor among all other composites with (7.012). Perlon reinforcement has the lowest amount of Safety Factor with the Epoxy matrix with (1.11).

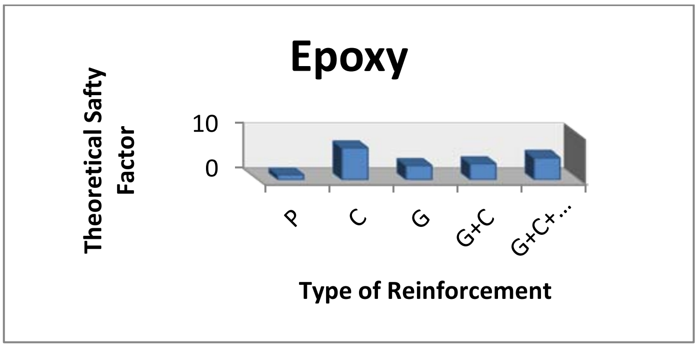


Figure 17: Theoretical safety factor of Epoxy matrix composites with various reinforcement

7. Conclusions

The results show that changing the type of reinforcement has a great influence on the measured properties and as follows: Young's modulus (E) and ultimate tensile strength of (Epoxy + Carbon reinforcement) is the highest with tensile strength values: (2.586 and 60.7) respectively. The highest fatigue and strain energy limit, safety factor is obtained in Epoxy with Carbon reinforcement composite with (42.7) MPa and (48.61) Joul/mm^3 and (6.9581) , respectively. Lowest amount of total deformation is obtained in Epoxy with [Hybrid (Glass + Carbon)+ SiO_2 particles composite with (1.467) mm. Reinforcement with perlon gave the lowest values in all measured properties. (Epoxy + Carbon reinforcement) composites gave optimum experimental, numerical and theoretical results which make them the best candidate to improve the fatigue characteristics of trans-tibial prosthetic socket.

References

1. T.A. Current, G.F.Kogler and D.G.Barth, "Static Structural Testing of Trans-Tibial composite sockets", Prosthetic and Orthotics international, Vol.23, pp.113-122, (1999).
2. Ahmed Aladdin Ibrahim, "Development and Testing of Syme Prostheses with Enhanced Structural Strength", PhD Dissertation, Mechanical Eng. Dept., University of Technology, Baghdad, Iraq, (2000).
3. Sam L.Philips and William Craelius,"Material Properties of Selected Prosthetic Laminates", Journal of Prosthesis and Orthotics, Vol.17, No.1, (2005).
4. Samira K.Radi, Haider F. Neama: "Analysis of a Below Knee Prosthetic Socket ", J. Eng. and development vol.12, No.2, pp.127-135, June (2008).
5. Samir Hashim Ameen, "Numerical and Experimental Investigation of Ankle-Foot Orthoses using (Perlon-Carbon Fibers-Acrylic) Materials", PhD dissertation, College of Engineering of Nahrain University, Baghdad, Iraq, (2011).
6. Ansys-11 Wokbench help guid, SAS IP, Inc., Eleventh Edition, (2008).
7. H. E. L. Kadi and F. Ellyin, "Effect of Stress Ratio on the Fatigue of Unidirectional Glass/Epoxy Composite Laminatae", Journal of Composites, Vol.25, No.10, pp.917-924, (1994).
8. Internet,http://www.antonine-education.co.uk/physics_as /module_3/topic_6/topic_6_elastic, (2010).
9. Gong Tao and Zihui Xia,"Biaxial Fatigue Behavior of an Epoxy Polymer with Mean Stress Effect", International Journal of Fatigue, Vol.31, pp.678-685, (2009).
10. www.webs1.uidaho.edu/"Fatigue Analysis of Combined Loading Mode", (2010).
11. www.maelabs.ucsd.edu/.../Materials/.../solutions/MESPD-Solution-manual. pdf. "Materials: engineering, science, properties, and design Solution manual", (2010).
12. Annual Book of ASTM Standard, "Standard Test Method for Tensile Properties of Plastics", D638-99, pp.1-12, (2000).
13. Alternating Bending Fatigue Machine instruction manual HSM20.
14. Diane Higgs, Phanvan Sanders and Yesh P.Singh, "Design Specifications of Lower Limb Prosthesis Socket", Proceedings of the ASEE Gulf. Southwest Annual Conference, (2002).
15. S.T. Peters, "Handbook of Composite", second addition, Chapman and Hall, (1998).
16. B. R. Varadharajan, W. N. P. Hung and H-J. Sue: "Fatigue of Epoxy a-Zirconium Phosphate Nanocomposites", Proceedings of the ASEE Gulph-Southwest Annual Conference Texas A&M University-Corpus Christi, (2005).
17. Oldapo A Aknyede, Ram Mohan, Ajit Kelkar and Jagannathan Sankar: "Static and Dynamic Loading Behavior of Hybrid Epoxy Composite with Alumina Nanoparticles", 16Th International conference on composite materials, (2010).
18. P.K. Mallick: "Fiber Reinforced Composites Materials, Manufacturing, and Design", by Taylor & Francis Group, LLC , 3rd edition, (2008).