IJRAME
ISSN (ONLINE): 2321-3051

INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING

Finite Element Analysis of Tensile and Fatigue Interaction in the Trans-tibial Prosthetic Socket

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Abstract

Five important laminated composite materials used for manufacturing trans-tibial prosthetic sockets were fabricated using vacuum molding technique. Epoxy was the matrix material of these composites, reinforced with five types of laced fibers and elements: perlon, glass, carbon, amalgam (carbon and glass) and amalgam (carbon and glass) with silica elements. Experiments were performed to measure different tensile and fatigue properties of the composite. The theoretical part of this work deals with calculations of the fatigue ratio and factor of safety. Fatigue and tensile behavior of composite socket material was predicted using ANSYS workbench and it was done by modelling five models for the socket which were treated as three-D structure composite materials. Performance of the composite socket material was inspected for perlon, glass, carbon, amalgam (carbon and glass) and amalgam (carbon and glass) with silica elements and it is found that epoxy with carbon reinforcement composites gives optimum experimental, numerical and theoretical results which make them the best candidate to improve the fatigue characteristics of trans-tibial prosthetic socket.

Keywords: Trans-tibial, Fatigue, ANSYS, Prosthetic, Finite element method

1. Introduction

The trans-tibial prosthesis has come a long way from the days of primeval wooden peg legs to present day electronically controlled prostheses, especially in the last decade, with advancements in anatomy, physiology, material design, computer technology etc. evident in new approaches in prosthetic sockets design, modern prosthetic knee mechanisms, more functional prosthetic feet and advanced manufacturing techniques. As well as an increase in patients' expectations, more and more requirements are placed on the prosthesis, above all on its functionality, reliability and safety. The prosthesis, in conjunction with an amputee, presents a complex biomechanical system, whose behavior is influenced by a few factors. In term of the prosthesis, the major factors are prosthesis alignment [1-5], the mechanical properties and alignment of the prosthetic foot [6, 7], the length of the prosthesis [8] and the weight of the prosthetic components. 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. Five different reinforcement materials and two resin type were used to construct the sockets. This paper 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+SiO2 elements] with Epoxy matrix. 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 [9].

2. Theory Section

Theory section of this article is based on the following Theories and Criteria:

2.1 Goodman line

The Goodman line is widely used as the criterion of fatigue failure when the when the component is subjected to mean stress as well as stress amplitude.

$$\frac{\sigma_m}{S_{ut}} + \frac{\sigma_a}{S_e} = \frac{1}{N}$$

Where σ_m = mean stress

σ_a = stress amplitude or Von Mises equivalent stress

S_{ut} = ultimate tensile stress

S_e = stress at endurance limit or fatigue limit

N = factore of safety

Mean stress σ_m is defined as

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

and alternating stress

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

2.2 Von Mises Equivalent Stress

Von Mises equivalent stress “allow the most complex stress value to be represented by a single quantity” and can be calculated by the following equation:

$$\sigma_{eq} = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 6({\tau_{12}}^2 + {\tau_{23}}^2 + {\tau_{31}}^2)}$$

Where

σ_{eq}= Von Mises equivalent stress
σ_1=principle normal stress in x-direction
σ_2= principle normal stress in y-direction
σ_3= principle normal stress in z-direction
τ_{12}= shear stress in xy-plane
τ_{23}= shear stress in yz-plane
τ_{31}= shear stress in zx-plane

2.3 Soderberg Criterion

$$\frac{\sigma_m}{S_y} + \frac{\sigma_a}{S_e} = \frac{1}{N}$$

Where σ_m = mean stress
σ_a = stress amplitude or Von Mises equivalent stress
S_{ut} = ultimate tensile stress
S_e = stress at endurance limit or fatigue limit
N = factore of safety

2.4 Strain Energy Criterion

The strain energy may be used as a fatigue failure criterion for different materials. The area under the stress strain graph is the strain energy per unit volume as shown in the following equition:

$$\Delta U = \frac{1}{2} \sigma \varepsilon$$

Where ΔU = strain energy per unit volume (J mm^{-3})
σ = stress developed (MPa)
ε = strain value (%)

2.5 Maximum Shear Stress Theory

The mathematical model of maximum shear stress theory[10] is as follows:

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2}$$

2.6 Fatigue Ratio

The fatigue ratio(R) is the ratio of the endurance limit to the tensile stress:

$$\text{Fatigue Ratio (R)} = \frac{Endurance\ limit\ (\sigma_e)}{Tensile\ strength\ (\sigma_t)}$$

3. Finite element method

A commonly used numerical analysis method in biomechanics is the finite element method, a computational approach for interface stress or structural deformation calculation evaluated in engineering mechanics. It has been introduced as a useful tool to understand the load transfer mechanics between a residual limb and its prosthetic socket. The finite element method is a full-field analysis for calculating the state of stress and elastic strain in the specific field. This technique is well suited for parametric analysis in the process of design [10-11].

In finite element modelling of lower-limb prosthesis, simulation of the contact between the limb and socket is a great challenge because there is sliding or friction action at the interface and the residual limb is donned into a socket with a different shape from the naked residual limb surface. In prior models, assumptions were made to simplify the problem. Out of many different simplifications, one is that the residual limb and prosthetic socket are fully connected as one body assigned with different mechanical properties. This will reduce the difficulties of modelling and computational time; however, this restricts any slippage at the interface and large in-plane stresses might develop at the limb surface. Another frequently adopted assumption is that the shapes of the residual limb and rectified socket are the same. Under this assumption, the socket shape variations aiming to redistribute the load to load-tolerant areas cannot be implemented in the finite element prediction. The stresses applied on the residual limb after donning into the rectified socket, were defined as pre-stresses [11]. Proximal regions of soft tissue and bones were fixed, and loading was applied at the prosthetic foot according to gait analysis data [12-13].

Since the finite element method was introduced in the late 1980s to design prosthetic socket, several models have been developed [14-18]. The prior finite element analyses have provided a better understanding of the effects of socket modifications, material properties of the sockets and liners alignment, residual limb geometry and mechanical properties, and frictional properties at the interface on the stress distribution over the residual limb. Finite element analyses can offer prediction of stress, strain and motion at any locations of the model and proficient parametric studies. Finite element technique has been identified as a useful tool to understand the load transfer mechanics between the residual limb and prosthetic socket [19-22].

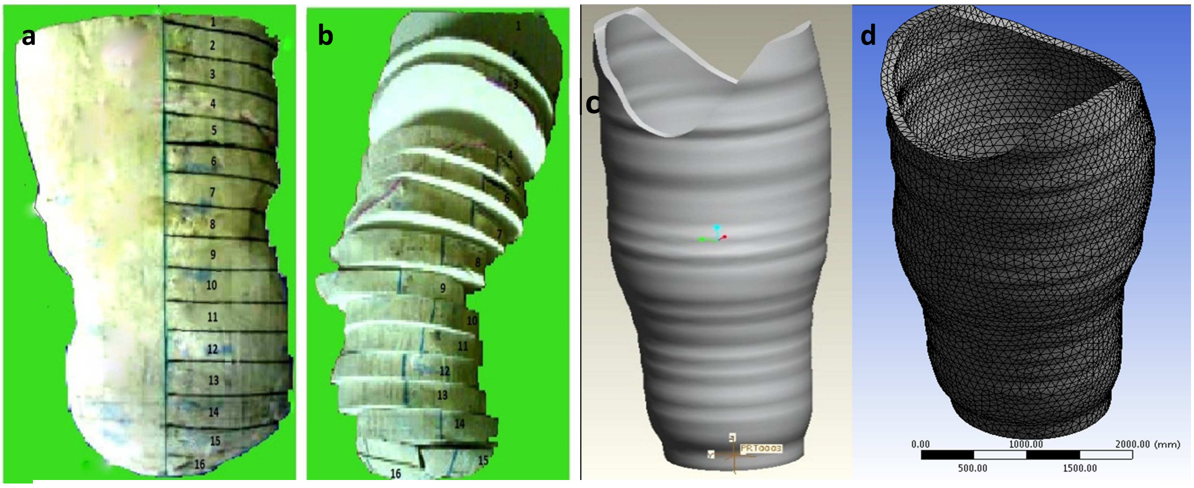


Figure 1: (a) Positive mold of prosthetic socket, (b) Discs of positive mold, (c) Pro-e model of prosthetic socket, (d) Mess view of prosthetic socket

4. Results and Discussion

4.1 Experimental Result

4.1.1 Fatigue Test

The Fatigue testing used by an alternating-bending fatigue testing machine with the specification of (fatigue testing machine HSM20, 1600 rpm, spanning voltage 240 V, frequency 50Hz, Normal power 0.6 Kw), and performed at room temperature and a stress ratio of R = -1 (tension– compression).

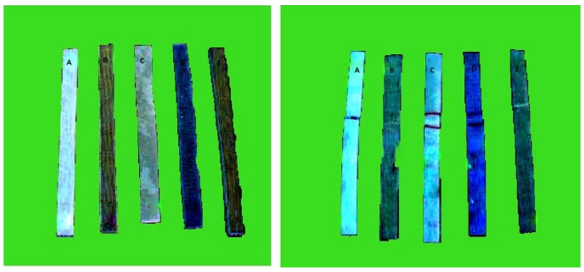


Figure 2: Fatigue experimental specimens before and after the test

Figure 2 shows the fatigue standard specimen test according to the machine's manual. The results of all fatigue tests carried out at various reinforcements are graphically displayed in the form of S-N curves shown in table 1 & 2. These curves are obtained by curve fitting the experimental data of fatigue test, using logarithmic formula [25].

Table 1 Fatigue stress vs. no. of cycle (S-N) curve

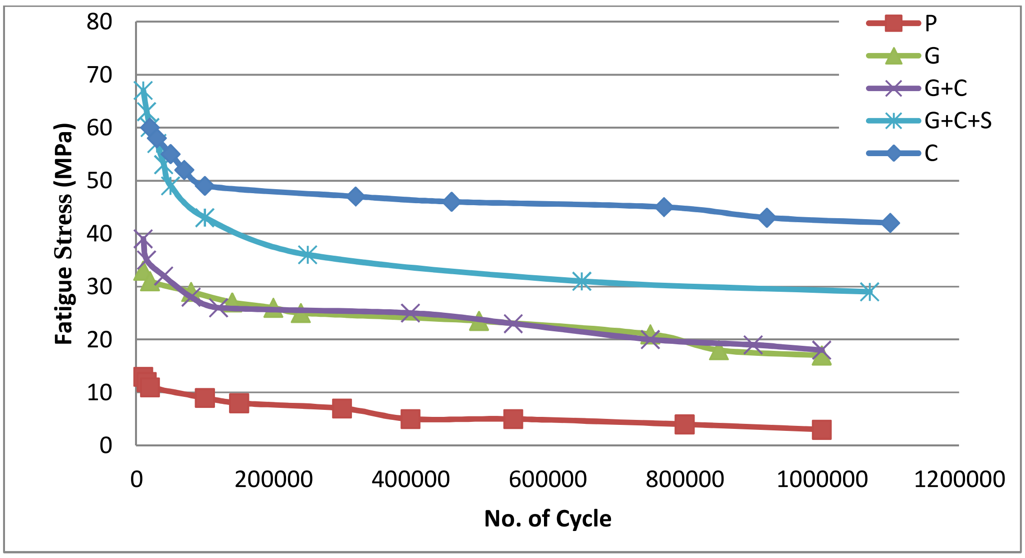
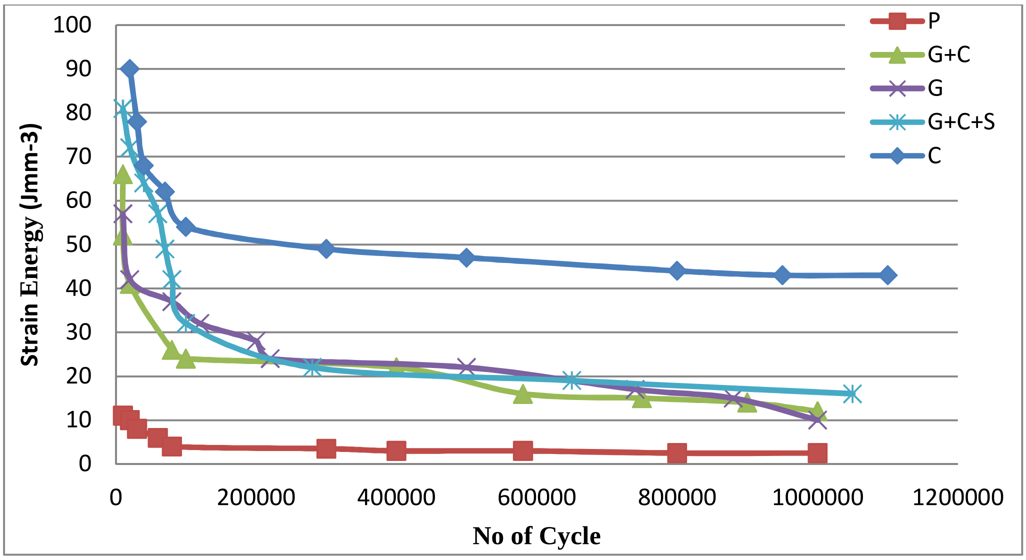
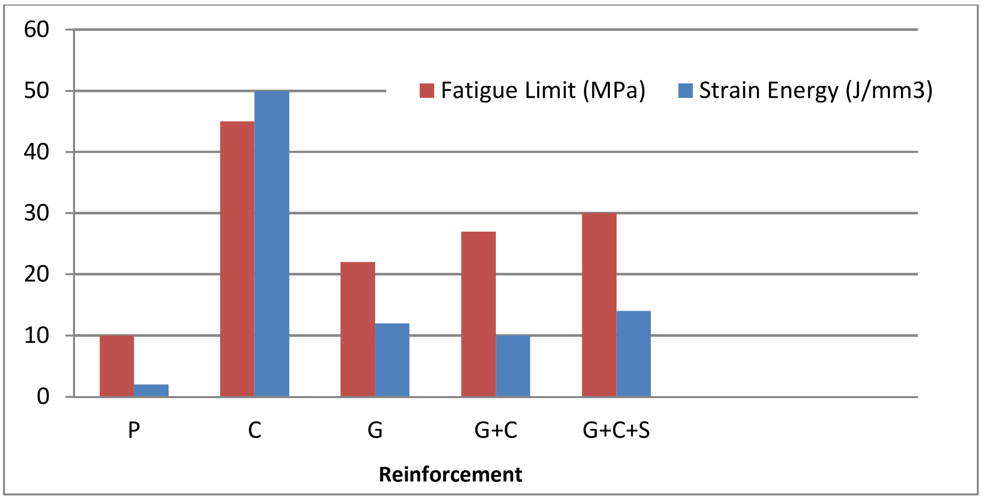


Table 2 Strain energy vs. no. of cycle (S-N) curve



The fatigue strength of the tested materials is taken at No. of Cycle of 10^6. Since, outside that No. of Cycles fatigue life becomes infinite. On the whole, the fatigue limit of materials is proportional to its tensile strength; hence materials with higher ultimate tensile strength possess higher fatigue limit. It is evident from table 1 that for all classes of laminates, reinforcement type has a noticeable influence on their fatigue resistance as shown in table 1 & 2. Carbon reinforcement provided the highest fatigue limit due to the high Young's modulus (E) and Ultimate tensile strength. Amalgam (Glass + Carbon)+ SiO_2 elements gave the second highest fatigue limit where the presence of SiO_2 elements rises the Young's modulus (E) and ultimate tensile strength of the material by obstructing the propagation of crack and the high bonding of Epoxy with the reinforcement. It is exemplified from the table that fatigue limit of Carbon reinforcement increases as much as eight times of magnitude as compared to perlon reinforcement.

Table 3 Fatigue limit and strain energy of epoxy matrix with different reinforcement



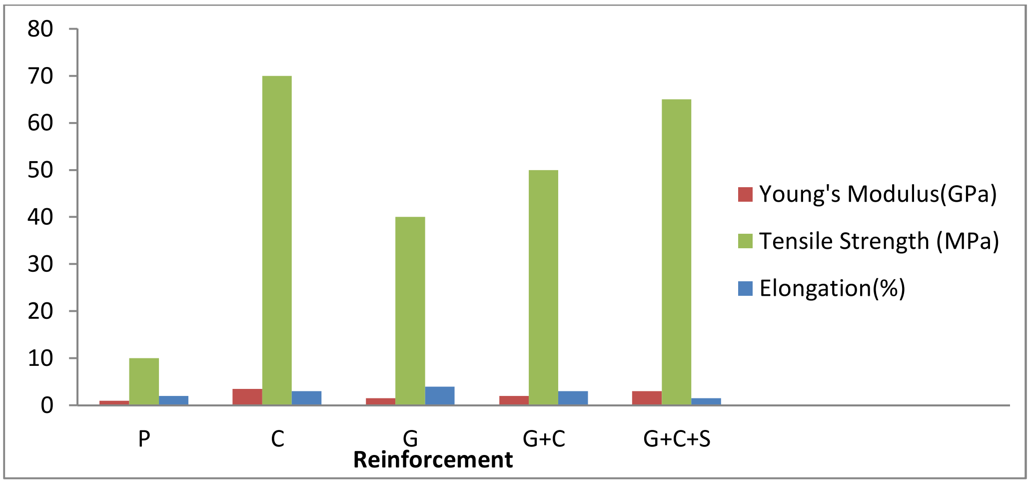
Both stress and strain were recorded from tension test and used to evaluate strain energy and plotted in table 2 & 3 respectively. It can be seen from the table that epoxy with carbon reinforcement composite have the highest strain energy with 50 J/mm^3, that is logical since their stress and strain 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. Similarly, it can be seen that the perlon reinforcement gave the lowest values of Strain Energy and Strain Energy limits among all composites with 2 J/mm^3. This behavior originates from the low tension properties of this type of reinforcement.

4.1.2 Tensile Test

Figure 3: Tensile experimental specimens before and after test

This test is performed according to (ASTM D638) at room temperature with (5 KN) applied load and strain rate of (1.5 mm/min). Figure 3 shows a tension standard specimen [24].

Table 4 Tensile properties of epoxy matrix with different reinforcement



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. Altering the type of reinforcement and matrix has a great influence on tensile properties. Tensile properties are shown in table 4. It can be seen from this table that reinforcing with carbon gives the optimum mechanical properties. Also adding SiO_2 elements to amalgam (Glass+Carbon) reinforcement increase the tensile modulus and tensile strength significantly by 1.5 and 1.7 time respectively when comparing with amalgam (Glass+Carbon) reinforcement alone and vice versa for elongation, because of the ability of epoxy to bond perfectly to a wide variety of fibers and the presence of SiO_2 elements obstructs the propagation of crack. 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 dominated in the overall behavior of the composites.

4.2 Numerical Result

4.2.1 Equivalent Stress and Shear Stress

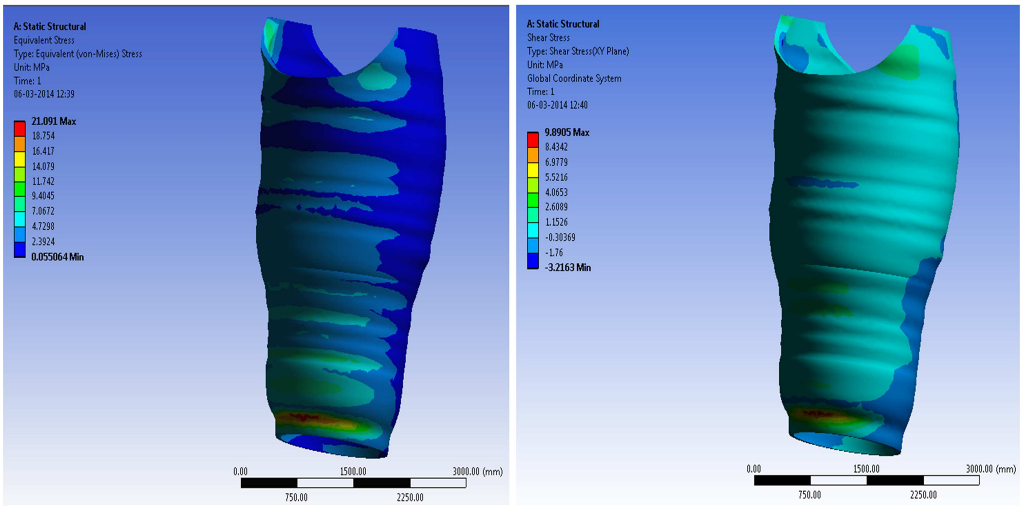


Figure 4: Curve plots of (a) equivalent stress and (b) shear stress

Equivalent alternating stress is the stress used to query the fatigue S-N curve after accounting for fatigue loading type, fatigue ratio effects in fatigue analysis. Equivalent alternating stress is the last calculated quantity before determining the fatigue life. Figure 4 (a) shows curve 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 4 (b) shows curve 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 maximum shear stress is concentrated in the lateral and basal planes of socket.

4.2.2 Total Deformation and Equivalent elastic strain

Figure 5 (a) 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 amalgam (Glass + Carbon) + SiO_2 elements composite. 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.

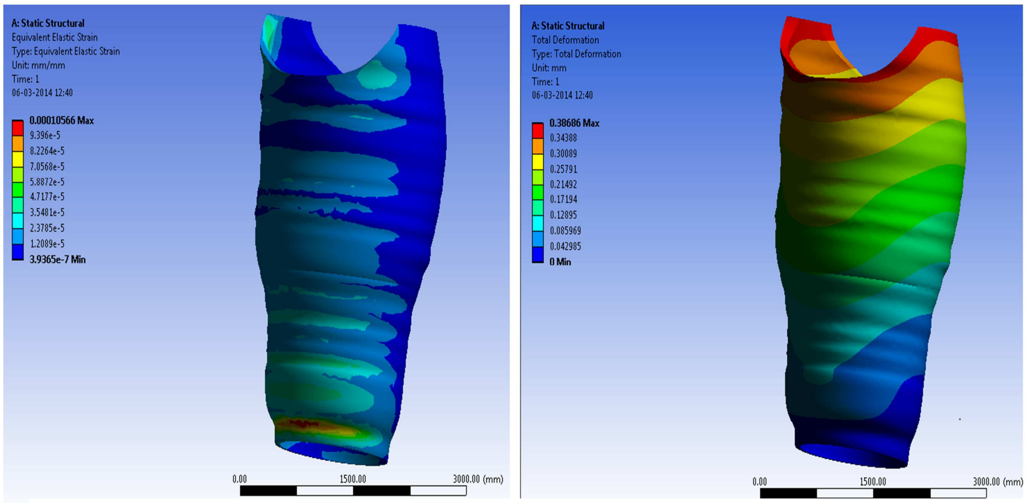


Figure 5: Curve plots of (a) equivalent elastic strain and (b) total deformation

4.2.3 Factor of Safety and Fatigue Life

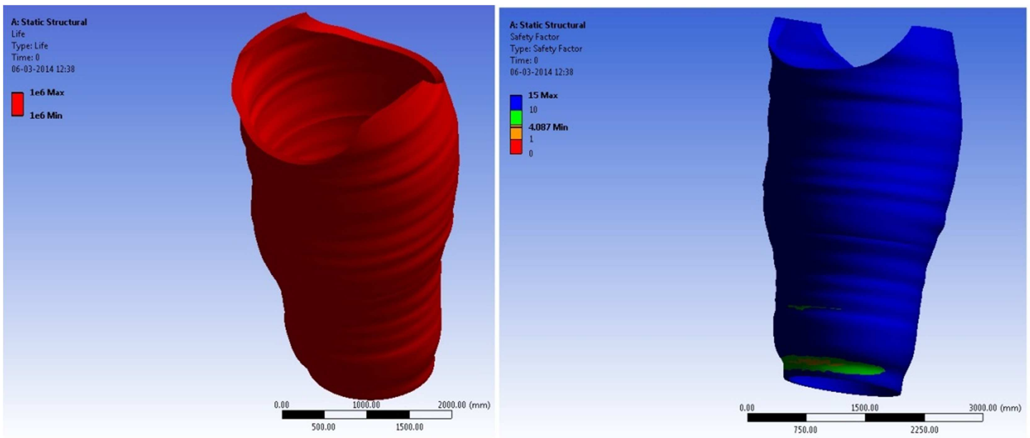


Figure 6: Curve plots of fatigue life and factor of safety

In ANSYS, maximum factor of safety displayed is 15, values less than one indicates failure before the design life has been reached. It can be noticed in Figure the distribution of safe and unsafe regions of the composites. Minimum safety factor of each composite is recorded in the mentioned figures above is 4.087, where as it can be seen that epoxy with carbon reinforcement composite had the maximum factor of safety.

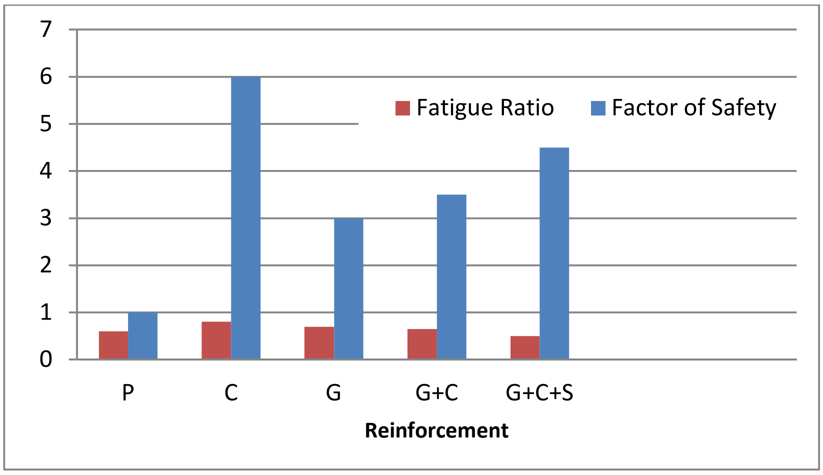
Fatigue life displays the available life for a given fatigue analysis. Counter plots shown in figure 6 were used to display the overall distribution of life throughout the socket for each type of composite used in this study. In stress life analysis with constant amplitude, if the equivalent alternating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

4.3 Theoretical Result

4.3.1 Factor of Safety

Factor of safety of the composite materials is obtained according to Goodman theory and table 5 shows the relationship between factor of safety and type of reinforcement used in this study, it can be seen from the table that the factor of safety of epoxy with carbon reinforcement composite give the highest factor of safety 6.0 among all other composites and perlon reinforcement has the lowest amount of factor of safety 1.0 with epoxy matrix.

Table 5 Fatigue ratio and factor of safety of epoxy matrix with different reinforcement



4.3.2 Fatigue Ratio (R)

Table shows the relationship between fatigue ratio and type of reinforcement, it can be seen from the table that fatigue ratio of epoxy matrix with carbon reinforcement composite was the highest value of 0.8. Since, tensile strength and fatigue limit of epoxy with carbon reinforcement have the highest experimental value, hence value of fatigue ratio coincide with the experimental result.

5. Conclusion

Results obtained by changing the type of reinforcement have a great influence on the measured properties like Young's modulus and ultimate tensile strength of epoxy matrix with Carbon reinforcement has the highest values 3.5 GPa and 70 MPa respectively. The highest fatigue limit, strain energy limit and safety factor obtained in epoxy matrix with carbon reinforcement are 45 MPa, 50 Jmm^{-3} and 6 respectively. Lowest amount of total deformation 1.5mm is obtained in epoxy matrix with glass, carbon and SiO2 reinforcement. On the basis of the experimental, numerical and theoretical result it can be concluded that epoxy matrix with carbon reinforcement will gives the optimum result to improve the fatigue characteristic of lower limb prosthetic socket.

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