

Development of Transfemoral Prosthetic Socket Utilizing Woven Raffia Palm Fibre-Groundnut Shell Powder Epoxy Hybrid Composite

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Abstract: Transfemoral amputation, also known as above-knee amputation, is a surgical procedure that involves the removal of a limb above the knee joint, such an individual requires a transfemoral prosthetic socket which accommodates the residual limb (stump) to enable the attachment of artificial limbs. In this research, a prototype transfemoral prosthetic socket was developed from raffia palm fibre-groundnut shell powder/epoxy hybrid composite using the hand lamination technique. Raffia palm fibre and groundnut shell powder were chemically treated with 0.1 mol NaOH solution at room temperature. Raffia palm fibre was weaved in 0/90° fibre orientation mat and the groundnut shell was crushed to powder of size 300 µm. The hybrid composite was developed by lamination lay-up technique. Three samples were laminated using 1-layer of woven raffia palm fibre and 1.9% of groundnut shell powder, 2-layers of woven raffia palm fibre and 3.8% of groundnut shell powder and 3-layers of woven raffia palm fibre and 5.7% of groundnut shell powder. Samples of the hybrid composite were characterized by subjecting them to fracture toughness test, impact resistance test, fatigue life test and compressive test. The results showed that 2-layers of woven raffia palm fibre and 3.8% of groundnut shell powder epoxy hybrid composite had optimum mechanical properties; fracture toughness 35.70 MPa, impact strength 18.04 MPa, fatigue life 1.3×10^3 cycles to failure at 600 MPa applied stress, the compressive strength in the composite was 13.73 MPa. Consequently, 2-layers of woven raffia palm fibre and 3.8% of groundnut shell powder was deployed in the lamination of prototype transfemoral prosthetic socket. Results of the finite element analysis (FEA) of prototype socket showed equivalent Von Mises stress maximum value of 26.661 MPa. The simulated total average deformation in the socket 54.79 mm. The maximum value of the maximum principal stress in the socket 13.936 MPa. The maximum value of the safety factor in the socket was 15. The simulated values confirm that the socket is optimized by use of natural fibres without compromising socket performance. Based on the results obtained from the research, it is recommended that 2-layer woven raffia palm fibre-groundnut shell/epoxy (2-layer woven RPF-GNS/Epoxy) hybrid composite be deployed for lamination of prosthetic sockets.

Keywords: Transfemoral, Prosthetic socket, Raffia palm fibre, Groundnut shell particulate, Hybrid composite.

1. INTRODUCTION

Prosthetic sockets produced from synthetic fibre reinforced composites have good mechanical properties however, the use of glass fibre in prosthetic sockets have negative side effects. According to Kitila and Wolla (2022); Tile and Nyior (2023) the presence of fibre glass causes sensitivity to the skin (skin itch) of the patient when it comes in direct contact with the skin. For the workers who produce the sockets, it causes skin allergies and allergic bronchitis which may lead to lung cancer (Tile *et al.*, 2024).

In addition, these synthetic fibres; have high density, are costly, stiff, and rigid (Tile *et al.*, 2024). The utilization of high density synthetic fibres in lower limb prosthetic sockets results in adverse consequences, including: increased risk of skin abrasion and discomfort on the residual limb and higher energy expenditure for users, leading to increased fatigue and reduced mobility. Also, the high carbon composition of these synthetic fibres causes problems to the environment as they are non-degradable (Ipilakyaa *et al.*, 2024).

In recent years, there has been a paradigm shift towards the use of sustainable and biocompatible materials in prosthetic design (Miller *et al.*, 2021). The need for environmentally friendly solutions and materials that are compatible with human tissue, minimizing the risk of skin irritation and allergic reactions, drives this transition (Kitila and Wolla, 2022). Such materials also offer the potential for enhanced comfort and user acceptance, which are critical factors in the successful adaptation of a prosthetic limb. The utilization of natural fibre-reinforced polymers in prosthetic socket lamination represents a significant innovation in this domain (Jagadish *et al.*, 2020). According to Ipilakya *et al.* (2024) and Tile *et al.*, (2024) prosthetic sockets made from natural fibre reinforced composite are biocompatible, have low weight, less costly, less stiff compared to conventional synthetic fibre polymer composite, and more comfortable for users.

According to Cheung *et al.* (2009) materials for prosthetic applications should have sufficient strength, light weight, resistance to thermal conditions, durability and be biocompatible to human tissues; it should not cause allergic reactions to the body. This is an application where natural fibres can be deployed; natural fibres have unique advantages over synthetic fibres such as; low cost, low density, high strength and stiffness to weight ratio, noncorrosive, processing flexibility, renewable, biodegradable, sustainable, non-toxicity and abundantly available (Chaudhary *et al.*, 2018).

Recent studies (Opeoluwa *et al.*, 2018; Tile and Nyior, 2023; Ipilakya *et al.*, 2024; Bam *et al.*, 2025) show that, raffia palm fibre is safe, non-toxic, has good specific strength, light weight, readily available, renewable, environmentally friendly, low cost, skin-irritation free, and good adhesion with resin with sufficient mechanical properties and could be used as a source of reinforcement in polymer composite applications where moderate strength and stiffness are required. Tile *et al.* (2024) studied the characterization of alkaline treated groundnut shell particulate for reinforcement in polymer composite for production of prosthetic sockets. The study showed that, groundnut shell is amorphous, biocompatible, safe and suitable for deployment as a filler in polymer composites for prosthetic sockets material. Addition of groundnut shell particulate to polymer composites has the potential to reduce thermal conductivity, and increase the glass transition temperature in the composites (Sesugh *et al.*, 2019).

This research, has evaluated woven raffia palm fibre and groundnut shell particulate/epoxy hybrid composite for the lamination of transfemoral prosthetic leg socket, to replace the glass fibres currently used by manufacturers of the prosthetic sockets. The composites samples and the prototype socket are produced by lamination lay-up technique.

2. MATERIALS AND METHODS

2.1 Materials

The materials used for this research include Epoxy resin (885) part A, Hardener (995) part B, Raffia palm fibres, Groundnut shells, Sodium hydroxide (NaOH), Distilled water, Laminating Leather (mould release agent), Hand gloves, POP Bandage, POP Powder, Stockinet, CAD model and a FEA software program.

2.2 Methods

The following experimental procedure were followed in the research.

2.2.1 Preparation of Raffia Fibre and Groundnut Shell Powder

The raffia palm fibres used in this research were treated in line with Tile and Nyior (2023). The fibres were weaved into bidirectional 0/90° fibre mat. Plate 1(a) shows the photograph of woven raffia palm fibres.



(a)

(b)

Plate 1: (a) Photograph of Woven Raffia Palm Fibre Mat (b) Photograph of Alkaline Treated Groundnut shell powder

Groundnut shell powder was treated in line with Tile *et al.* (2024). The powder was sieved using standard test sieves to a particulate size of 300 µm. Plate 1(b) shows the photograph of alkaline treated groundnut shell powder.

2.2.2 Production of Woven Raffia Palm Fibre and Groundnut Shell Reinforced Epoxy Hybrid Composite Samples

Production of the hybrid composite was carried out by lamination lay-up method. Wooden mould of 180 × 130 × 8 mm³ was used for producing the composite. The mould was covered with a lining (lamination leather) as mould release agent. Woven Raffia palm fibres were cut based on the mould dimensions and laid in the mould by hand layer by layer until the required thickness were obtained. Three plates were laminated based on 1-layer woven raffia palm fibre with 1.9% groundnut shell powder, 2-layer woven raffia palm fibre with 3.8% groundnut shell powder and 3-layer woven raffia palm fibre with 5.7% groundnut shell powder. Epoxy resin (885) part A and the hardener (995) part B were mixed in the ratio of 2:1 and stirred for 15 minutes to enable effective reaction. Volumes (3.52, 7.04, and 10.56) cm³ of groundnut shell powder as presented in Table 1, were measured using a beaker and added to the epoxy resin and the mixture was again stirred for 10 minutes before it was poured onto the woven raffia palm fibre mat in the mould. The fibre became saturated with epoxy resin and a roller used to ensure good compaction and freedom from porosity. The mould was closed and kept under pressure at room temperature for 24 hours before the composite was removed from it. Photograph of laminated samples shown in Plate 2, were cut for the various tests.



Plate 2: Photograph of Woven Raffia Palm Fibre-Groundnut Shell Reinforced Epoxy Hybrid Composite

Table 1: Composition of the Hybrid Composite

RPF Mat No. of Layers	RPF Mat Volume (cm ³)	GNS Particles Volume (cm ³)	Reinforcement (%)	Epoxy Resin Volume (cm ³)	Volume of Sample (cm ³)
1	3.52	3.52	3.8	180.16	187.2
2	7.04	7.04	7.5	173.12	187.2
3	10.56	10.56	11.3	166.08	187.2

2.2.3 Evaluation of the Hybrid Composite for Transfemoral Prosthetic Socket

Fracture Toughness Test

The fracture toughness test was done as per ASTM D-5045 in line with Sattar *et al.* (2023) using the 3-point bending fixture, utilizing centre loading on a simple supported beam. The pre-crack length initiated on the sample was 2 mm. The test was performed using 100 kN capacity universal materials testing machine. The dimension of the sample was 100 mm × 30 mm × 8 mm³. The sample was placed on two supports and was loaded by means of a loading nose midway between the supports and the deflection of the sample was recorded. Five samples were tested and the average values of the loads and deflections were obtained.

Impact Test

The unnotched Charpy impact test was conducted according to the ASTM D-256 in line with Sattar *et al.* (2023). The specimen dimensions were 75 mm x 8 mm x 7 mm³. In this method, the unnotched specimen is supported horizontally as a simple beam and fractured by a blow delivered in the middle of the specimen by the pendulum. Five samples were tested and the average of the values of the energy required for fracture in joules was recorded by a dial gauge, which is fitted on the machine.

Fatigue Test

The Flexural fatigue test was performed according to ASTM D-790 in line with Djamel and Bachir (2024). The sample size was $50 \times 8 \times 7 \text{ mm}^3$. The specimen was held as a cantilever beam in a vice at one end and was bent by a concentrated load applied through a yoke fastened to the opposite end. A counter was used to record the number of cycles along with a cut-off switch to stop the machine when the specimen failed. The test was carried out by first determining the complementary mass and effective mass of the test specimen. The load required to produce the desired stress was calculated from these values. The number of cycles required to produce failure was determined. A curve of stress versus cycles to failure (S-N diagram) was plotted from the test results.

Compression Test

Compression test was conducted according to ASTM D3410 in line Van *et al.* (2015). Universal (digital) compression testing machine was used. The dimension of the sample was $25 \text{ mm} \times 25 \text{ mm} \times 8 \text{ mm}^3$. Two load blocks in the machine exerted a compressive force on the test specimen with a test speed of 2 mm/min. Then for each sample, two moduli were determined, one for the front and one for the backside. These were averaged to determine the compression modulus and strain for each composite specimen.

2.2.4 Socket Lamination Procedure Using 2-layer Woven Raffia Palm Fibre-Groundnut Shell Powder/Epoxy Hybrid Composites

The prototype transfemoral prosthetic socket was laminated using the sample with the optimum mechanical properties (2 layers of woven raffia palm fibre-groundnut shell powder/epoxy hybrid composites) in line with Bhagirath and Makarand (2022). The prosthetic socket was custom made by taking critical measurements from a male patient with a right leg amputation; age 46 years old and mass 64 kg (translating into a weight of 627.84 N). Measurements carried out using mediolateral calliper included; the stump (residual limb circumference) 558.8 mm, distal end of stump circumference 355.6 mm and length of stump 393.7 mm. In the lamination of the socket, the layup of materials through layers were as follows:

1. Over the positive mould, a bag of Poly Vinyl Acetate (PVA) was applied; this serves as a refiner for the inner surface of the socket and provides protection for the lamination process, this eliminates the risk of resin leak over the positive mould as shown in plate 3(a). The protective PVA bag also functions as a medium to vacuum out negative pressure as air bubbles and voids between layers during the lamination process. Voids impair and reduce socket strength.
2. Once the PVA bag was placed, two layers of cotton stockinette of thickness 0.2 mm each were laid up to the required thickness of socket.
3. Over the stockinette layers, 2 layers of woven raffia palm fibre mat were applied covering the entire mould followed by repeating layers of stockinette as shown in plate 3(b).
4. After the outermost stockinette layer, a layer of PVA bag is applied which forms a medium through which the epoxy resin can be incorporated into the laminate.
5. The matrix material is prepared by mixing epoxy of 115.41 cm^3 with a pigment to add colour, hardener in a 2:1 ratio of epoxy to hardener mixed before adding groundnut shell particulate.
6. The process continues with the pouring of the matrix mixture into the arrangement of socket material through the pouring channel of the outer PVA. The matrix mixture dampens the layered composition of the socket material and is evenly distributed with manual manipulation. The vacuum machine was turned on and adjusted to a pressure of 80 bar until all the matrix mixture had seeped into the socket material evenly and there was no visible air trapped.
7. After the lamination process was completed the fabricated socket was allowed to dry at room temperature. The epoxy resin was cured for 24 hrs. When the socket had dried, it was removed from the positive mould. The plate 3(c) shows the photograph of the laminated prototype socket.

2.3 Modelling of the Prototype Socket using Finite Element Analysis

The model of the above knee prosthetic socket was drawn using solid works software based on patients' actual geometry and dimensions, and imported into the ANSYS software. The load applied to the prosthetic limb in the finite element model was static and equal to the body weight of 637 N of user with a fixed support at the adapter of socket. The ANSYS work bench software was then used to obtain the solution. Von Mises stress analysis, maximum principal stress, total deformation and the fatigue safety factor of the socket simulated simulated.

3. RESULTS AND DISCUSSION

3.1 Fracture Toughness of the Composite

The results of the fracture toughness are presented in Table 2. The results of the hybrid composite shows; fracture toughness (K_{IC}) ranged from 14.16-35.70 MPa \sqrt{m} . 1 layer of woven RPF-GNS/Epoxy hybrid composite gave fracture toughness (K_{IC}) value of 20.31 MPa \sqrt{m} . The fracture toughness (K_{IC}) increased to a maximum value of 35.70 MPa \sqrt{m} upon reinforcement of 2 layers of woven RPF-GNS/Epoxy. The value of the fracture toughness reduced to 14.16 MPa \sqrt{m} upon the reinforcement of 3 layers of woven RPF-GNS composites. This could be attributed to insufficient wetting of the fillers as a result of the addition of more filler material in the composite (Nyior *et al.*, 2018).

According to Harsha and Satish (2022) high values of fracture toughness indicate better resistance to crack initiation and propagation. Fracture toughness is particularly important for prosthetic sockets designed to bear weight, such as lower limb sockets. This means, prosthetic socket materials with high fracture toughness are less likely to develop cracks or fractures during normal use and can withstand the repetitive loading associated with weight bearing activities leading to increased durability, safety and longevity of the prosthetic socket contributing to the overall functionality and comfort of the socket for the user (Quintero and Zasulich, 2019).



(a)

(b)



(c)

Plate 3: Photograph of; (a): Positive Cast (3-D model) of the Stump Covered with PVA bag (b): Positive Cast (3-D model) of the Stump Covered with 2 layers of woven raffia palm fibre mat (c): Photograph of the Laminated Transfemoral Prosthetic Prototype Socket

The results of the fracture toughness of the composites, indicates that, the maximum fracture toughness is obtained in the sample with 2 layers of woven RPF-GNS/Epoxy hybrid composites with 35.70 MPa \sqrt{m} .

Table 2: Result of the Fracture Toughness Test
Crack Length = 2 mm

Sample	Load (N)	Fracture Toughness(KIC) (MPa√m)
1layer RPF-GNS	330	20.31
2layer RPF-GNS	580	35.70
3layer RPF-GNS	230	14.16

3.2 Impact strength of the composite

Materials having high impact strength prevents catastrophic failure of the socket during use, reducing the risk of accidents and injuries to the user (Sattar *et al.*, 2023). The results of the impact strength of the hybrid composite are presented in Table 3. The results show; impact strength ranged from 15.12-18.04 MPa. 1 layer of woven RPF-GNS/Epoxy hybrid composite had impact strength value of 16.10 MPa. The impact strength increased to a maximum value of 18.04 MPa upon reinforcement of 2 layers of woven RPF-GNS/Epoxy. The value of the impact strength reduced to 15.12 MPa upon the reinforcement of 3 layers of woven RPF-GNS/Epoxy. The analysis of the impact strength results of the composites material shows maximum impact strength of 18.04 MPa in the sample containing 2 layers of woven RPF-GNS/Epoxy hybrid composites. According to Sattar *et al.* (2023) the high impact strength of the sample indicates that, the material can absorb and dissipate impact forces effectively, reducing the likelihood of sudden failure or fracture. This leads to a more durable prosthesis that can withstand the stresses associated with daily activities and occasional accidents. The prosthetic socket material needs to have an excellent ability to withstand impact forces which provides safety and high resistance to breakage from impact load from the residual limb (Monette *et al.*, 2020).

Table 3: Result of the Impact Strength Test

Sample	Energy at break (kJ)	Area of Sample (m ²)	Impact Strength (kJ/m ²)
1layer RPF-GNS	0.033	0.00205	16.10
2layer RPF-GNS	0.037	0.00205	18.04
3layer RPF-GNS	0.031	0.00205	15.12

3.3 Fatigue Life of the composite

The results of the fatigue test are presented in Figure 1(a-c). Fatigue occurs when a material is subjected to cyclic loading, causing damage which may progress to failure. The fatigue damage for composite materials consists of cracks and deformation. The cracks form after a few cycles even if the loads are insignificant (Djamel and Bachir, 2024). According to Kahtan *et al.* (2015) majority of the failure of prosthetic components are fatigue related under cyclic walking loads. The results of the fatigue tests of the composites are graphically displayed in the form of S-N curves. The results of the 1 layer of woven RPF-GNS/Epoxy hybrid composite showed the sample endured a stress of 1750 MPa with 0.2×10^3 cycles to failure and a lower stress of 600 MPa with 0.6×10^3 cycles to failure. The results of the 2 layers of woven RPF-GNS/Epoxy hybrid composites showed the sample endured 1790 MPa, 1200 MPa, and 600 MPa with various cycles of 0.3×10^3 cycles, 0.7×10^3 cycles, and 1.5×10^3 cycles to failure. This is the sample that is able to endure higher cycles to failure at various test stresses thus having a better fatigue life among the samples. The results of the 3 layers of woven RPF-GNS/Epoxy composites showed; the sample subjected to 1500 MPa with 0.2×10^3 cycles to failure, at a stress of 1000 MPa the number of cycles to failure was 0.4×10^3 cycles and at 500 MPa the cycles to failure increased to 1.2×10^3 cycles.

It is clear from the results that, the sample with the 2 layers of woven RPF-GNS/Epoxy hybrid composites gave better life. The results of the fatigue test show that, at high stresses, the sample endured low number of cycles to failure. At lower stresses, the samples endured higher number of cycles to failure. This trend is in agreement with the works of Djamel and Bachir (2024), when the applied stress is high, the cyclic fatigue failure number (N) of the composite material decrease. It was observed and as expected, the curves clearly show that low number of cycles are needed to cause fatigue failures at high stress levels while low stress levels can result in sudden, unexpected failures after a large number of cycles. The fatigue life (N_f) of a material is defined by the total number of stress cycles required to cause failure.

The lifetime for prosthetic socket depends on the applied stress and the composite material type (Abbas, 2018). Fatigue test is important for prosthetic socket materials because it helps evaluate their durability, strength, and performance under repetitive cyclic loading conditions that simulate the daily usage of prosthesis by amputees. Prosthetic sockets are subjected to various stresses and strains during activities such as walking, running, climbing stairs, which can lead to wear, deformation or failure over time.

3.4 Compressive strength of the composite

The results of the compressive test of the composites are presented in Table 4. Prosthetic socket materials should have sufficient compressive strength to withstand the loads and forces encountered during daily activities while providing adequate support and comfort to the user (Bhagirath and Makarand, 2022). Table 4 show; compressive strength ranged from 5.28-13.73 MPa. 1 layer of woven RPF-GNS/Epoxy hybrid composite had a compressive strength value of 13.15 MPa. The compressive strength increased to a maximum value of 13.73 MPa upon reinforcement of 2 layers of woven RPF-GNS/Epoxy. The value of the compressive strength reduced to 5.28 MPa upon the reinforcement of 3 layers of woven RPF-GNS/Epoxy.

The analysis of the compressive test results of the composites material shows that, 1 layer of woven RPF/Epoxy composites and 2 layers of woven RPF-GNS/Epoxy hybrid composites had good compressive strengths of 13.15 and 13.73 MPa respectively. The results indicate that, these samples have high stiffness compared to other samples. This means that, the samples can withstand moderate compressive forces without significant deformation or failure ensuring the socket remains functional and reliable over time to provide adequate support for the residual limb during daily activities (Quintero and Zasulich, 2019).

3.5 Finite Element Analysis of the Prototype Socket

Simulation of the prototype transfemoral prosthetic socket using finite element analysis was done in four stages in accordance to Chiad and Tahir (2017); drawing of the geometry of the socket in Auto CAD which is based on actual measurements of the patient, meshing in ANSYS software, applying the boundary conditions and the loads, and reviewing the results.

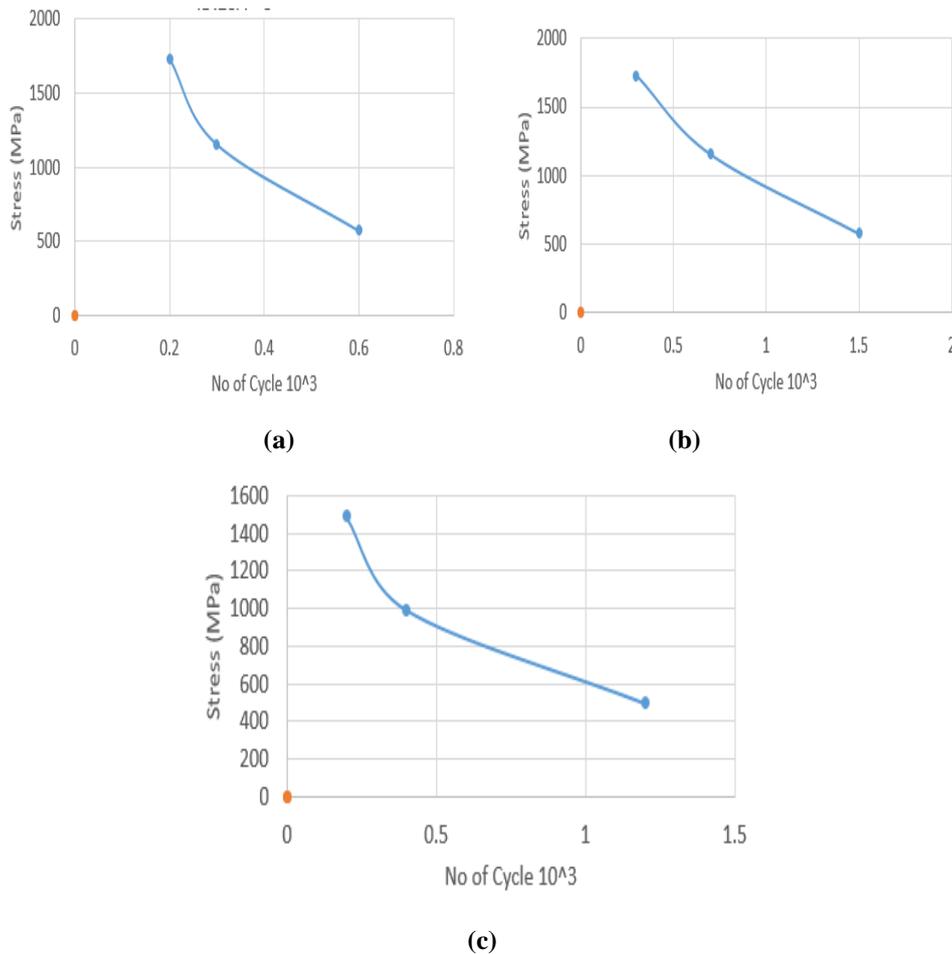


Figure 1: (a): Stress/No. of Cycles of 1 Layer of Woven RPF-GNS/Epoxy Hybrid Composite

(b): Stress/No. of Cycles of 2 Layers of woven RPF-GNS Epoxy Hybrid Composite

(c): Stress/No. of Cycles of 3 Layers of Woven RPF-GNS Epoxy Hybrid Composite

Table 4: Compressive Properties of the Composite

Sample	Maximum Compressive stress (MPa)	Compressive strain at Maximum Compressive stress (%)
1layer RPF-GNS	13.15	18.22
2layer RPF-GNS	13.73	11.47
3layer RPF-GNS	5.28	22.27

Detailed parameters of the finite element model for prosthetic socket are shown in Table 5 and the material properties used for finite element analysis of prosthetic socket are presented in Table 6.

Table 5: Detailed Parameters of the Finite Element Model for Prosthetic Socket

Parameters	Details
Analysis Type	Static
Mesh Type	Solid Mesh
Support	Fixed Support
Material Model Type	Linear Elastic Isotropic
Mesher used	Standard Mesh
Number of Elements	13382

The ANSYS was used as a numerical tool to simulate the behaviour of the prosthetic socket and evaluate Von Mises stresses, total deformation, fatigue life, safety factor and mesh sensitivity analysis. This is important for the optimization and improvement of prosthetic socket performance. According to Chiad and Tahir (2017) this helps to identify areas of high stress concentration and potential failure points, allowing for design modifications to optimize stress distributions. This information can guide the selection of materials with better mechanical properties, ensuring durability and longevity of the socket (Quintero and Zasulich 2017).

Table 6: Material Properties Used for Finite Element Analysis of Prosthetic Socket

Property	Value
Density of Material (g/cm ³)	1.4
Young's modulus (MPa)	184.93
Modulus of elasticity (MPa)	1701.39
Poisson's ratio	0.31
Ultimate Tensile Strength (MPa)	10.80

According to Hasan *et al.* (2016) one of the important steps in finite element modelling is mesh sensitivity. This was done to ensure that the mesh density is fine enough for the mesh to converge. This process is shown in Figure 2. By plotting a curve of maximum principal stresses against number of elements and total deformation against number of elements. The mesh sensitivity analysis showed that the mesh converged with 13382 elements. The results of the mesh sensitivity obtained in the simulation is in agreement with the simulated maximum principal stresses with average value of 0.60304 MPa and the total deformation in the socket with an average value of 54.79 mm with 13382 elements.

Figure 3(a) shows the geometry of the prototype socket, Figure 3(b) shows the model of the prosthetic socket with meshing. On the meshed model applied load was 637.84 N (weight of user), fixed support was applied at the distal end of the socket. The loading conditions are shown in Figure 3(c).

Equivalent Von-Mises stresses (also known as the Von Mises yield criterion) showed the amounts of stress and spread in the socket. The model of the socket showed 26.661 MPa as the maximum Von Mises stress in the socket as seen in Figure 4(a). Equivalent Von Mises stress values typically correlates with deformation and strain in the material.

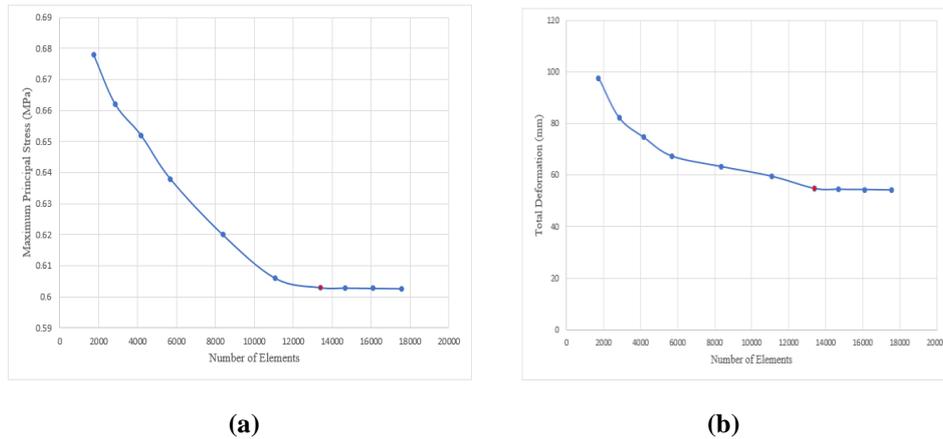


Figure 2: Mesh Sensitivity Plot (a) Maximum Principal Stress vs No. of Elements (b) Total Deformation vs No. of Elements

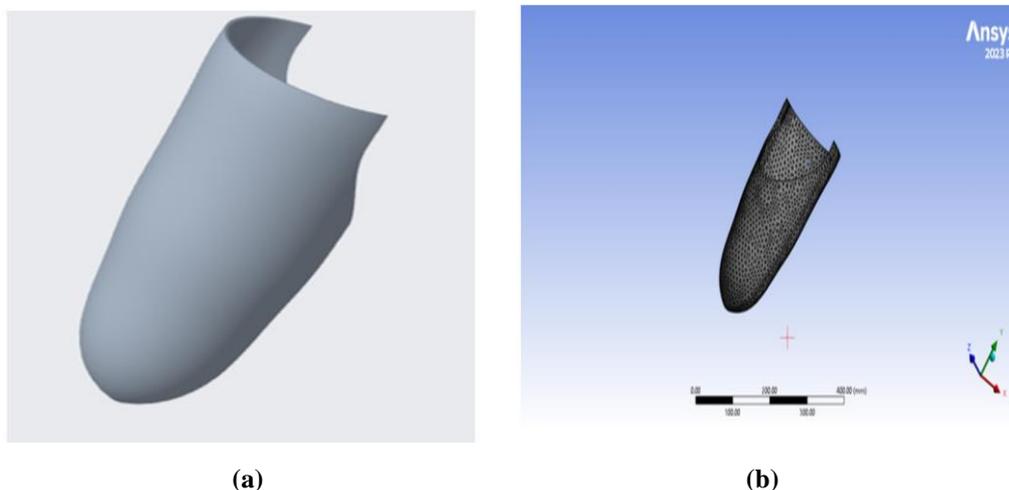
Maximum Principal stress values indicate the maximum normal stress experienced by the material at any given point. The normal stresses are the direct tensile and direct compressive forces. The maximum value of the maximum principal stress in socket is 13.936 MPa as shown in Figure 4(b). The value of the Maximum Principal Stress in the simulation of a prototype prosthetic socket can provide valuable insights into the socket performance and potential areas for improvement (Gubbala *et al.*, 2021).

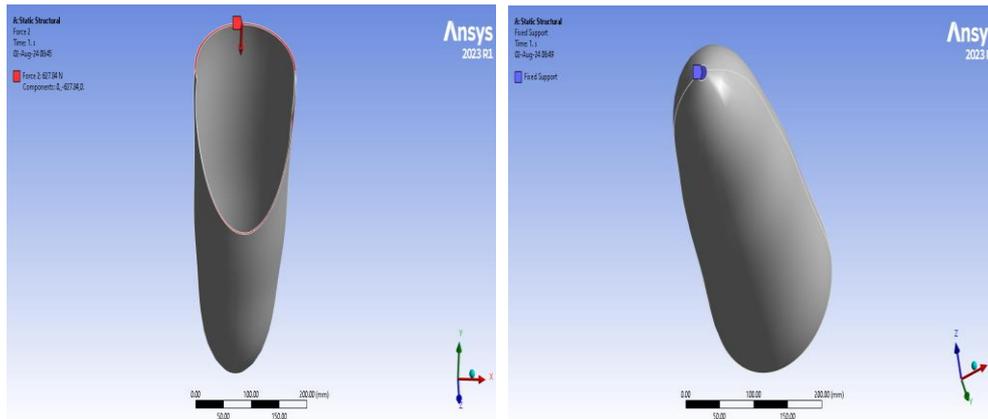
Values of maximum total deformation of the socket is shown in Figure 4(c), it is found that the maximum deformation is 130.63 mm (0.131 m). The maximum value is found at the top of socket. The socket displayed an overall moderate deformation with an average value of 54.79 mm as confirmed by the mesh sensitivity check. Large deformations in prosthetic sockets is undesirable as it can lead to an improper fit between the residual limb and the socket, causing discomfort, skin irritation, and a reduced mobility for the user (Quintero and Zasluch, 2017).

The maximum value of safety factor in the finite element analysis was 15 as shown in figure 4(d). According to Majdi *et al.* (2018) values less than one indicate failure before the design life has been reached. According to Abbas (2018) the high value of the safety factor in the simulation of the socket indicates a high level of safety and reliability built into the design. This is a confirmation that, the socket can withstand loads significantly higher than those expected during normal use thus, reducing the risk of failure due to unexpected or extreme loading conditions.

4. CONCLUSION

The study evaluated the fracture toughness, impact resistance, fatigue life and compressive properties of hybrid composite material for transfemoral prosthetic socket produced from a blend of alkaline treated raffia palm fibres and alkaline treated groundnut shell powder using epoxy resin as matrix. The result indicates; fracture toughness ranged from 14.16-35.70 MPa, impact strength ranged from 15.12-18.04 MPa, fatigue life ranged from 600 MPa/ 0.5×10^3 cycles to failure – 600 MPa/ 1.5×10^3 cycles to failure and compressive strength in the composite ranged from 5.28-14.15 MPa.



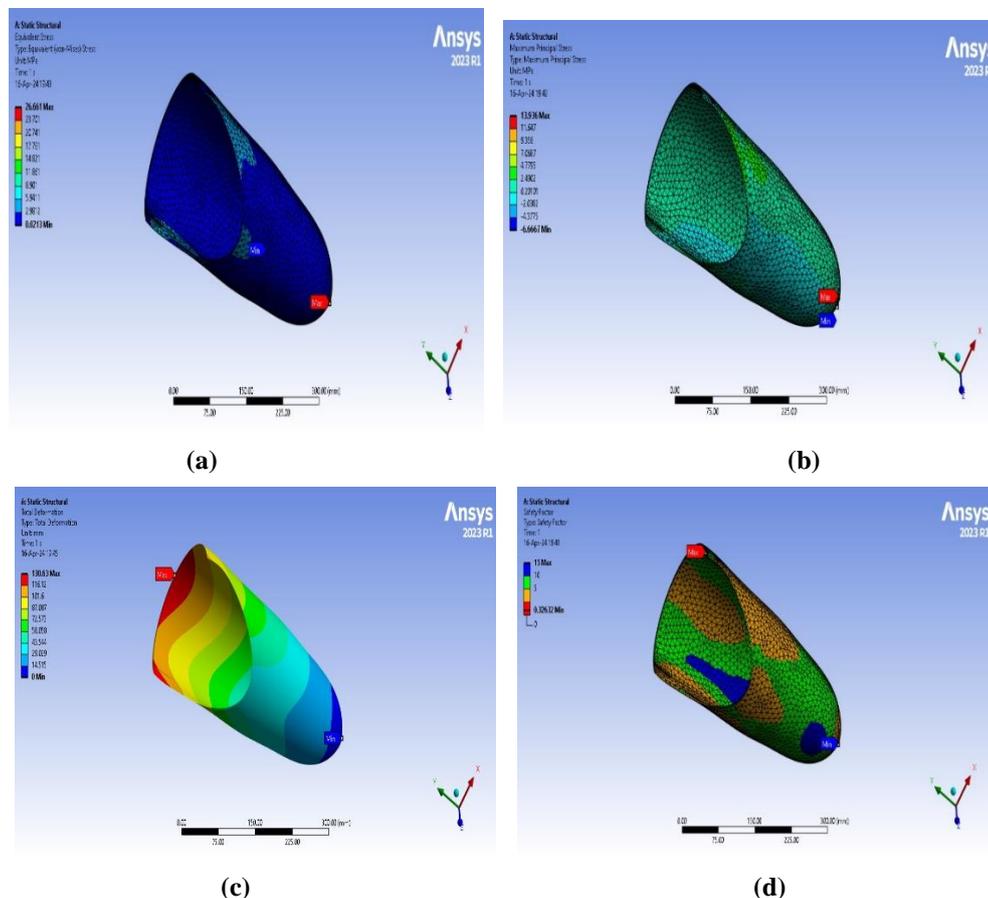


(c)

Figure 3: (a) Geometry of the Transfemoral Prosthetic Socket (b): Model of the Transfemoral Prosthetic Socket with Meshing (c): Loading Conditions for Prosthetic Modelling

The results established that 2-layers of woven raffia palm fibre and 3.8% of groundnut shell powder reinforced epoxy hybrid composite had optimum mechanical properties; fracture toughness 35.70 MPa, impact strength 18.04 MPa, fatigue life 1.3×10^3 cycles to failure at 600 MPa applied stress, the compressive strength in the composite was 13.73 MPa. Consequently, 2-layers of woven raffia palm fibre and 3.8% of groundnut shell powder was deployed in the lamination of prototype transfemoral prosthetic socket.

Results of the finite element analysis (FEA) of prototype socket showed equivalent Von Mises stress maximum value of 26.661 MPa. The simulated total deformation in the socket showed moderate deformation, with average total deformation in the socket 54.79 mm. The maximum value of the safety factor in the simulated socket was 15. The simulated values confirm that the socket is optimized by use of low density natural fibres without compromising socket performance.



(a)

(b)

(c)

(d)

Figure 4: (a) Von Mises Stress (b): Maximum Principal Stresses (c) Total Deformation (d) Fatigue Safety Factor

This is particularly important for prosthetic sockets, where weight, durability, cost and biocompatibility are critical factors affecting user comfort and accessibility. Based on the results obtained from the research, it is recommended that 2-layer woven RPF-GNS/Epoxy hybrid composite be deployed for lamination of prosthetic sockets.

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