

Effect of Composition and Thickness of Finite Element Analysis (FEA) of Prosthetic Leg Socket Developed from Composite of Banana Fibre Reinforced Epoxy Resin

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Abstract: This study investigates the effect of fibre composition and wall thickness on the finite element (FE) structural performance of a banana pseudo stem fibre reinforced epoxy composite developed for below - knee prosthetic socket application. Banana fibres were extracted, treated with alkali (NaOH) and characterised using FTIR, EDXRF and XRD to confirm the effectiveness of the treatment. Composites were fabricated by hand lay -up at five fiber loading (0,10,20, and 40 wt%), and mechanically tested to obtain input properties such as density, Young's modulus, poisson's ration, tensile, flexural and compressive strength for ANSYS workbench. A representative total surface bearing below knee socket geometry was modeled at five wall thickness (3-7mm), producing a full factorial design of 25 simulation cases evaluated under ISO10328 ultimate (2240N) and serviceability (1000N) loading. Results show that Von Misses stress and total deformation decrease with increasing wall thickness, with deformation additionally reduced at higher fibre content, while factor of safety improves with fibre loading up to 30wt% (S3) before declining at 40wt%(S4) due to fibre agglomeration and reduced inter facial bounding. All 25 cases remained viable structurally under ultimate loading, with the S3 composition at 5mm thickness offering the best balance of strength, deformation control and wearable mass (Fos $\approx$ 2.72). The findings demonstrate that alkali - treated banana fibre reinforced epoxy is a mechanically viable, environmentally sustainable and low-cost alternative to imported socket material, offering a practical pathway toward improving prosthetic accessibility in resource constrained settings.

Keywords: *Banana Pseudo Stem Fibre; Epoxy Composite; Below Knee Prosthetic Socket; Finite Element Modeling; Sustainable Biomaterials.*

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I. INTRODUCTION

Globally, amputation represents a growing public and substantial health change. Estimate from [1-2] indicates that approximately 445 million people are living with amputation related conditions globally, which reflects a significant burden of long-term disability and functional limitation. Lower limb amputation (LLA) is one of the major contributors to this burden and is commonly associated with traumatic injuries, diabetics melitus and peripheral vascular disease [3-4]. In Nigeria, hospital-based studies have

documented lower limb amputation as a major clinical challenge, with diabetic foot disease identified as one of the leading indications for amputation, including the below knee and above knee procedures, performed frequently among patients that are affected [5-6]. These findings reveal that lower limb amputation is a recurring healthcare burden in Nigerian hospitals and not an isolated clinical event [7-8].

Access to prosthetic devices remains substantially inadequate, hence the major challenge associated with limb loss is the limited ability of many amputees to regain

functional mobility due to inadequate access to appropriate prosthetic rehabilitation services. Thus, only small portion of people requiring prosthetic care in low- and middle-income settings receive appropriate devices. In Africa, the demand for lower limb prosthetic services continues to exceed available capacity due to high costs, shortages of trained prosthetist and orthotist, dependence on imported components and limited availability of prosthetics and orthotics centers [9-10]. Studies have reported that the cost of prosthetic components and rehabilitation services frequently exceeds what many amputees can afford. This results in low rates of prosthetic adoption among those who require them. This challenge represents a major public health concern because unmet prosthetic and rehabilitation needs are associated with reduced mobility, social exclusion, restricted participation and increased social economic vulnerability [9,11].

Aside the challenge of access to prosthetic devices, the socket remains one of the most critical components of a lower limb prosthesis because it provides the primary mechanical connection between the residual limb and the structure. However, socket related problems such as discomfort, reduced function and prosthetic abandonment are faced by users of this device [12-13]. Clinical and engineering studies on socket design have identified challenges such as excessive interface pressure, discomfort during prolonged use, poor socket fit, tissue breakdown, skin irritation and progressive material degradation under repeated loading conditions. Investigations of the socket residual limb interface indicate that excessive localized pressure, socket weight, shear force and inadequate structural performance can reduce stability, negatively influence long term prosthetic use and increase fatigue [8,9,14]. The materials commonly used in socket fabrication also possess significant engineering compromises. Thermoplastics such as polypropylene remain widely used because they are inexpensive, lightweight, easily mouldable and suitable for fabrication in resource constrained environment, however, there are concerns regarding fatigue behaviour, creep deformation and long-term mechanical stability under repetitive loading.[15]. Fibre reinforced composite material, particularly carbon fibre-based composites, provide superior mechanical stiffness, strength and fatigue resistance compared with conventional thermoplastic, but their high cost and dependence on imported materials limit widespread application in many low- and middle-income countries. Furthermore, carbon fibre production is associated with considerable environmental impacts compared with some alternative reinforcement materials, creating additional sustainability concerns in prosthetic manufacturing [16]. For developing countries, such as Nigeria, where limited access to imported prosthetic components, foreign and exchange constraints, and inadequate local manufacturing capacity remain persistent challenges, the development of socket materials which combine local manufacturability, affordability, adequate mechanical performance and environmental sustainability remains an important unresolved research challenge.

Despite decades of research in composite materials, this challenge has persisted because development in sustainable

composite material and prosthetic socket engineering have progressed as distinct research domains. Natural fibre reinforced polymer composite, including banana, pineapple fibre systems, jute, have received extensive research attention as potential alternatives to synthetic fibre composites due to their renewable origin, low density, reduced environmental impact and relatively low production cost [17-18]. Studies have shown that natural fibre composite can provide competitive mechanical properties when appropriate fibre selection, surface treatment, fibre orientation and matrix compatibility are achieved [19-20]. Prosthetic socket engineering has increasingly adopted Finite Element Analysis (FEA) as an important computational approach for evaluating socket stresses, interface mechanisms, design optimisation and deformation behaviour under controlled loading conditions [15]. Many existing FEA studies of prosthetic socket have focused mainly on conventional thermoplastics, laminated composite and synthetic fibre reinforced material rather than natural fibre composites which are sustainable [12]. Reviews of prosthetic manufacturing technologies have identified the integration of sustainable fibre reinforced composites with advanced numerical modelling techniques as an important but still underdeveloped research direction for future socket design. On the other hand, banana cultivation generates substantial quantities of pseudo stem biomass after harvesting, much of which remains under utilised despite its high cellulose content and potential as a renewable fibre resource [21]. Studies have demonstrated that banana pseudo stem fibres possess favorable mechanical and morphological characteristics for composite reinforcement, although their industrial application is limited due to challenges related to fibre processing, treatment optimisation, variability and inadequate engineering validation[18]. Therefore, banana fibre represents an accessible renewable material whose transition from agricultural biomedical application requires integrated studies which combine chemical treatment, mechanical characterisation, material modelling and component level analysis.

This study addresses the gap in literature by investigating the effect of composition and wall thickness on finite element performance of a banana fibre reinforced epoxy composite designed and evaluated as below knee prosthetic socket. By adopting a combined experimental and computational research design, this study will determine the mechanical properties of selected composites, prepare banana fibre reinforced epoxy composites at predetermined fibre loadings, characterise the treated fibre to confirm the effectiveness of alkali treatment, develop a representative below knee prosthetic socket geometry and simulate it in ANSYS work bench across all fibre wall thickness and determine the effect of fibre composition and wall thickness on the socket structural response. The findings of this study will be useful for prosthetic fabricators. Economically and environmentally, the study demonstrates a pathway toward sockets made from an abundant, near Zero cost agricultural byproduct rather than imported carbon fibre or thermoplastic, hence directly addressing the cost barrier identified as the dominant obstacle to prosthetic access across low resource regions.

II. MATERIALS AND METHOD

➤ Research Design

This study adopts an experimental and Computational research design which comprises four sequential stages. A summary of the workflow is presented in Figure 1.

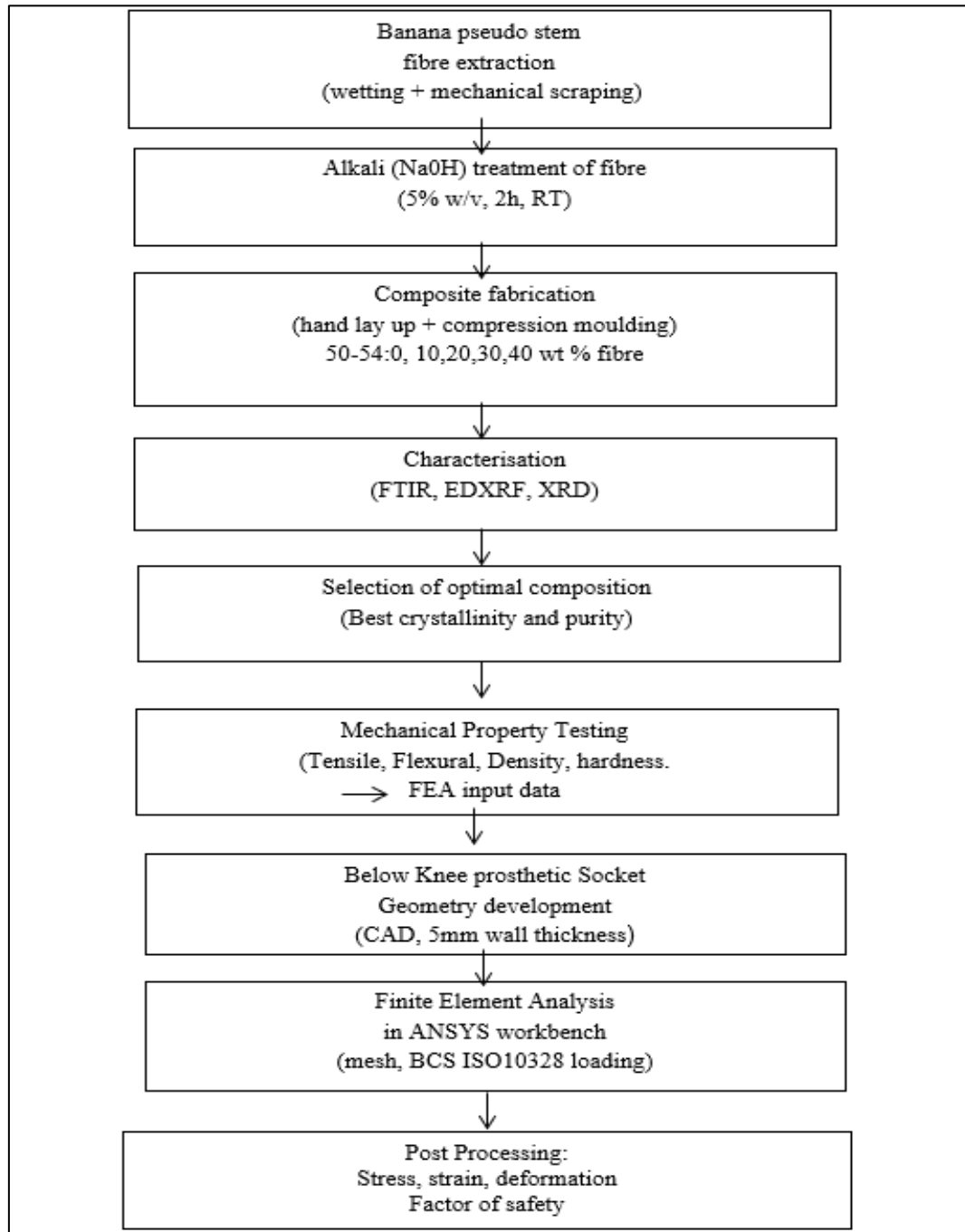


Fig 1 Schematic Workflow of the Research Methodology

➤ Materials

The material used for this study are banana pseudo stem fibre, diglycidylether of bisphenol -A type epoxy resin (which is commercially designated as LY556 or equivalent), Amine - based hardener (HY951) triethylenetetramine, Sodium hydroxide (NaOH) pellets, distilled water, a silicon/wax-based release agent, acetone and mould surface.

➤ Extraction and Treatment of Banana Fibre

• Fibre Extraction

Fibre was manually extracted from the pseudo stem sheaths using the wetting and scraping method. The outer sheaths were peeled and wetted in water for 7-10 days in order to loosen the non-fibrous matter, then scraped manually to separate the fibre bundles. The fibre extraction was washed

in clean water and dried in the sun for a period of 60 hours to reduce the moisture content before finally oven drying at a temperature of 60°C for 2 hours before composite fabrication.

- *Alkali (NaOH) Treatment*

In order to improve fibre-matrix adhesion by removing surface impurities such as waxy substances, lignin, hemicellulose and to increase surface roughness, the dried fibres were treated with a 5% (W/V) NaOH solution for 2 hours at room temperature, at a fibre to solution ratio of 1:18. The fibres were washed thoroughly with distilled water, a

neutral PH, neutralised with a dilute acetic acid, rinse where necessary was achieved. The neutralised fibre was again dried in an oven at 60°C for 24 hours.

➤ *Composite Formulation and Characterisation*

To investigate the effect of composition, the treated banana fibres were incorporated into the epoxy matrix at five fibre holding level by weight. The composition matrix is shown in Table 1.

Table 1 Composite Formulation Matrix

Sample ID	Banana Fibre Content (wt%)	Epoxy Resin System (wt%)
S0 (Control)	0	100
S1	10	92
S2	20	82
S3	30	85
S4	40	63

Author's Compilation

- *Fabrication Method*

Composite were fabricated using the hand lay-up technique, followed by light compression moulding. A wooden mould (200mm x 200mm x 4mm) cavity was cleaned and coated with a release agent. The hardener and epoxy resin mixed in the ratio of 1:8 and stirred manually for 6 minutes to ensure homogeneity and minimization of air entrainment. A calculated mass of treated banana fibre of average length between 25 - 35mm, randomly oriented was layered into the mould in alternating layers with the resin mixture, with a manual rolling between layers in order to remove entrapped air and achieve uniform wetting. The mould was closed and a compressive load of approximately 0.05MPa was applied to reduce void content and control laminate thickness. Curing was carried out at room temperature (25± 2°C) for 24 hours, followed by post-curing at 60°C for 4 hours, and then demoulding. Cured laminates were cut into standard specimen sizes for characterization and mechanical testing using a diamond-tipped cutter based on ASTM specifications.

- *Characterization Techniques*

Each composite formula (S₀ - S₄) was subjected to characterization tests to evaluate their chemical structure, elemental Composition and Crystallinity. They collectively determine the composition selected for socket development.

➤ *Fourier Transform Infrared Spectroscopy (FTIR)*

FTIR analysis was performed to identify functional group present in the treated and untreated fibre and the fabricated composites and to confirm the effectiveness of alkali treatment. Spectra were recorded on an FTIR spectrometer in the wave numbers range of 4000 - 400cm⁻¹ at a resolution of 4cm⁻¹, using the Attenuated Total Reflectance (ATR) method, with 32 scans co-added per spectrum as shown in Table 2.

Table 2 Key FTIR Absorption Bands of Banana Fibre and Epoxy Composites

Wavenumber (cm ⁻¹)	Assignment
3350	O-H stretching (cellulose, hemicellulose)
2910	C-H stretching (aliphatic)
1735	C=O stretching (hemicellulose; reduced after alkali treatment)
1620	Aromatic C=C (lignin)
1240	C-N (resin)
1045	C-O-C stretching (cellulose glycosidic linkage)
810	Unreacted epoxy

Author's Compilation

➤ *Energy Dispersive X-ray Fluorescence (EDXRF)*

EDXRF was used to determine the elemental composition of the fibre and composite surface particularly to verify removal of surface impurities after alkali treatment and to detect residual inorganic constituents associated with the plant fibres. Analysis was performed on an EDXRF

spectrometer with excitation voltage of 25kv, current of 500 µA, rhodium (Rh) tube and counting time of 180s per sample. Table 3 depicts the elemental composition of banana fibre based on the EDX/EDXRF analyzing.

Table 3 Elemental Composition of Banana Fibre (EDX/EDXRF)

Element	Approx. Content (wt%)
Carbon (C)	50
Oxygen (O)	46
Potassium (K)	1.5
Silicon (Si)	0.5
Magnesium, Phosphorus, Sulphur	< 1 each
Calcium (Ca)	0.9

Author's Compilation➤ *X-ray Diffraction (XRD)*

XRD was conducted to determine the crystallinity index of the banana composite. Diffractograms were obtained using an X-ray diffractometer operating at 40kv and 35mA over a scanning range of $2\theta = 40^\circ$ and step size of 0.02° at a scan rate of $2^\circ/\text{min}$. The crystallinity index was calculated using the Segal empirical method as shown in the equation 1.

$$CI(\%) = \frac{I_{200} - I_{am}}{I_{200}} \times 100 \quad (1)$$

Where:

- $CI(\%)$ = Crystallinity Index (percentage)
- I_{200} = Intensity of the crystalline peak (usually the (200) plane)
- I_{am} = Intensity of the amorphous region

The composition exhibiting minimal residual inorganic content by EDXRF, reduced amorphous impurity related to FTIR band and highest crystallinity index by XRD was selected for prosthetic socket development and finite Element Analysis (FEA)

➤ *Mechanical property Determination*

Beyond what FTIR / EDXRF XRD provides, FEA requires mechanical input properties such as elastic modulus,

poison ratio, ultimate tensile strength, hence standard mechanical tests were additionally conducted on selected banana composite to generate input data for ANSYS material model: tensile testing (ASTMD3039, 2mm/min cross head speed and 5 replicates). For flexural testing (ASTMD790, three point bending span to depth ration 16:1). For density (ASTM D792, Archimedes method) and hardness (shore D, ASTM D2240). The numerical values of mechanical properties in depicted in Table 4

➤ *Development of the Below - Knee Prosthetic Socket Geometry*• *Description of Residual Limb Socket Geometry*

A representative below knee residual limb geometry was used as the basis for socket design. In the absence of a patient specific 3D scan, an idealised total surface bearing (TSB) socket geometry was adopted and scaled to a length of 135mm below the knee of a proximal and distal circumference of 350mm and 240mm respectively. The outer geometry of the socket was modelled as a hollow, tapered, anatomically contoured shell in CAD environment using solid works based on the residual limb model with a uniform patellar -tendon bearing (PTB) relief region typical of trans-tibial sockets.

Table 4 Mechanical Properties Used as FEA Input

Property	Symbol	Value	Unit
Density	P	1190	kg/m ³
Young's Modulus	E	3.6	GPa
Poisson's Ratio	N	0.3	—
Ultimate Tensile Strength	Σ_{uts}	48	MPa
Flexural Strength	Σ_f	75	MPa
Shear Modulus	G	1.6	GPa
Compressive Strength	Σ_c	80	MPa
Hardness	Shore D	73	—

Author's Compilation

Table 5 FEA Simulation Parameters

Parameter	Values
Fibre composition level (S0-S4)	0, 10, 20, 30, 40 wt%
Wall thickness level	3, 4, 5, 6, 7 mm
Number of simulation cases	25 (5×5)
Ultimate load applied (all 25 cases)	2240 N (ISO 10328, P5)
Serviceability load (all 25 cases)	1000 N

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- *Thickness Variation*

To address the objective of evaluating the effect of thickness, the socket shell was modelled at five uniform wall thickness (3mm, 4mm, 5mm, 6mm and 7mm)

➤ *Finite Element Analysis (FEA) Methodology*

- *Software and modelling Environment*

FEA was carried out in ANSYS workbench. The socket CAD geometry was imported into ANSYS for geometry clean-up, then meshed and solved in ANSYS.

- *Materials Model Assignment*

The composite was modelled as a homogeneous isotropic and inelastic linear material using the properties in Table 2.5 and 2.4 as the engineering data input. A simulation was run for each of the five compositions (S_0 - S_4), for each thickness of (3mm to 7mm), which yields a full factorial design of 25 simulation cases as summarized in Table 6.

Table 6 Ultimate Load Case Results (2240 N, ISO 10328 Load Condition)

Case	Sample	t (mm)	σ_{eq} (MPa)	δ (mm)	ϵ (%)	FoS
1	S0	3	32.0	4.20	1.067	2.03
2	S0	4	27.4	1.77	0.913	2.37
3	S0	5	24.3	0.91	0.810	2.68
4	S0	6	22.0	0.53	0.733	2.95
5	S0	7	20.3	0.33	0.677	3.20
6	S1	3	32.0	3.50	0.889	1.81
7	S1	4	27.4	1.47	0.761	2.12
8	S1	5	24.3	0.76	0.675	2.39
9	S1	6	22.0	0.44	0.611	2.64
10	S1	7	20.3	0.28	0.564	2.86
11	S2	3	32.0	3.15	0.800	1.94
12	S2	4	27.4	1.33	0.685	2.26
13	S2	5	24.3	0.68	0.608	2.55
14	S2	6	22.0	0.39	0.550	2.82
15	S2	7	20.3	0.25	0.508	3.05
16	S3	3	32.0	2.86	0.727	2.06
17	S3	4	27.4	1.21	0.623	2.41
18	S3	5	24.3	0.62	0.552	2.72
19	S3	6	22.0	0.36	0.500	3.00
20	S3	7	20.3	0.23	0.461	3.25
21	S4	3	32.0	2.63	0.667	1.50
22	S4	4	27.4	1.11	0.571	1.75
23	S4	5	24.3	0.57	0.506	1.98
24	S4	6	22.0	0.33	0.458	2.18
25	S4	7	20.3	0.21	0.423	2.36

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(σ_{eq} = Equivalent (Von Mises) stress; δ = Maximum Total Deformation; ϵ = Strain; FoS = Factor of Safety.)

➤ *Meshing*

The socket geometry was discretized using 10 node tetrahedral solid elements which was suitable for the irregular curved geometry of the socket shell. A mesh convergence study was performed by refining the element size (10mm to 1mm). The Von misses stress was monitored until the change successive refinement fell below 5%. A converged element size of approximately 3mm with local refinement to approximately 1mm at the distal end and PTB region was adopted for all the 25 cases. Mesh quality was checked using orthogonal quality (> 0.1) and skewness (< 9) metrics

➤ *Boundary Conditions and Loading*

The proximal rim of the socket was constrained as a fixed support which represents attachment to the prosthetics limb system. A compressive axial load which represents body weight during the stance phase of the gait was applied at the distal end of the socket. A statics load of 2240N was adopted as the ultimate load case for this study. A 1000N load case was included as a lower bound serviceability load. Table 7 shows the serviceability load case results.

Table 7 Serviceability Load Case Results (1000 N)

t (mm)	σ_{eq} (MPa)
3	14.3
4	12.2
5	10.9

6	9.8
7	9.1

Author's Compilation

• Solution and Post Processing

Each of the 25 cases was solved for the ultimate and serviceability load condition. Output parameters such as stress, maximum total deformation, factor of safety and Von misses stress were extracted for comparison. Results were

tabulated and plotted as a function of fibre composition (wt%) and wall thickness(mm). This was done for the identification of the composition thickness combination that minimizes deformation and stress while still maintaining the socket mass/ thickness within a practical wearable range.

III. RESULTS AND DISCUSSION

➤ Effect of wall thickness on Von misses Stress

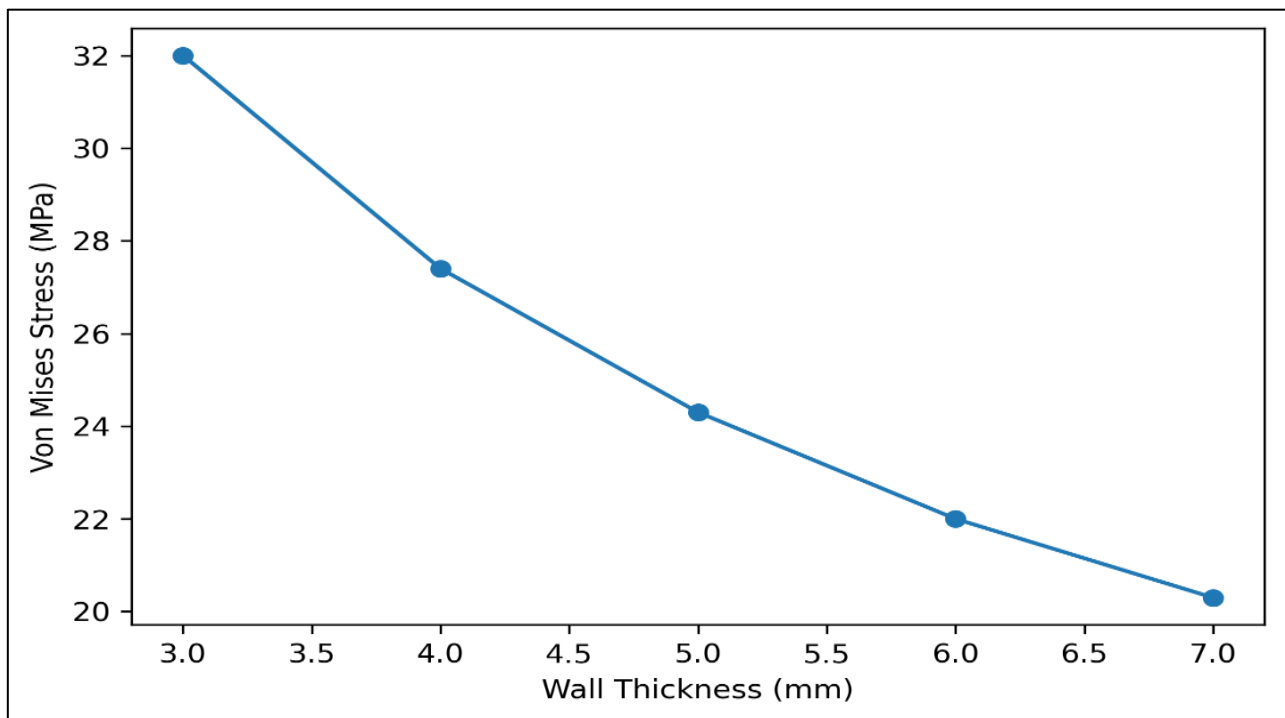


Fig 2 Von Misses vs. Wall Thickness

Figure 2 illustrates the relationship between Von Misses stress and socket wall thickness under an ultimate load condition of 2240N. Across the five fibre compositions, Von misses stress decreases non linearly as the wall thickness increases. A reduction of approximately 37% is observed as the von misses stress decreases from a maximum of 32.0Mpa at 3mm to a minimum of 20.3MPa at 7mm. The stress values of each thickness level are distinct across the five compositions, indicating that the composition of the socket wall thickness has negligible effect on the magnitude of stress developed under the given applied load. This behaviour is explained by the fact that the loading condition applied to the socket is a fixed, force-controlled boundary condition and not displacement-controlled condition.

The findings of this study show consistency in the effect of wall thickness and loading condition on the structural response of the prosthetic leg socket. Previous finite element study focused on stance phase loading where stresses were influenced by the interaction between the linear socket geometry, residual limbs at normal ambulation conditions

[15]. In contrast, this study applies ISO10328 structural loading which represents strength verification condition rather than routine walking. This condition produces more mechanical demands than a typical gait simulation. Hence, the higher Von Misses stress obtained in this study is primarily attributed to the difference in loading conditions and objectives.

Practically, the implication of this result is that, since the ultimate tensile strength of the composite (48Mpa) exceeds the highest recorded stress (32.0Mpa at 3mm), it implies that all the five thickness studies are structurally viable under the ISO10328 ultimate load, without the effects of composition dependent stress. This informs the designer to select wall thickness based on deformation, control mass and stiffness, rather than being constrained by stress failure at thin sections. This supports the use of lighter and thinner socket walls in order to improve the comfort of the wearer, metabolic cost usage, provided the stiffness and factor of safety related criteria are not compromised.

➤ *Effect of wall thickness and fibre composition on Total deformation.*

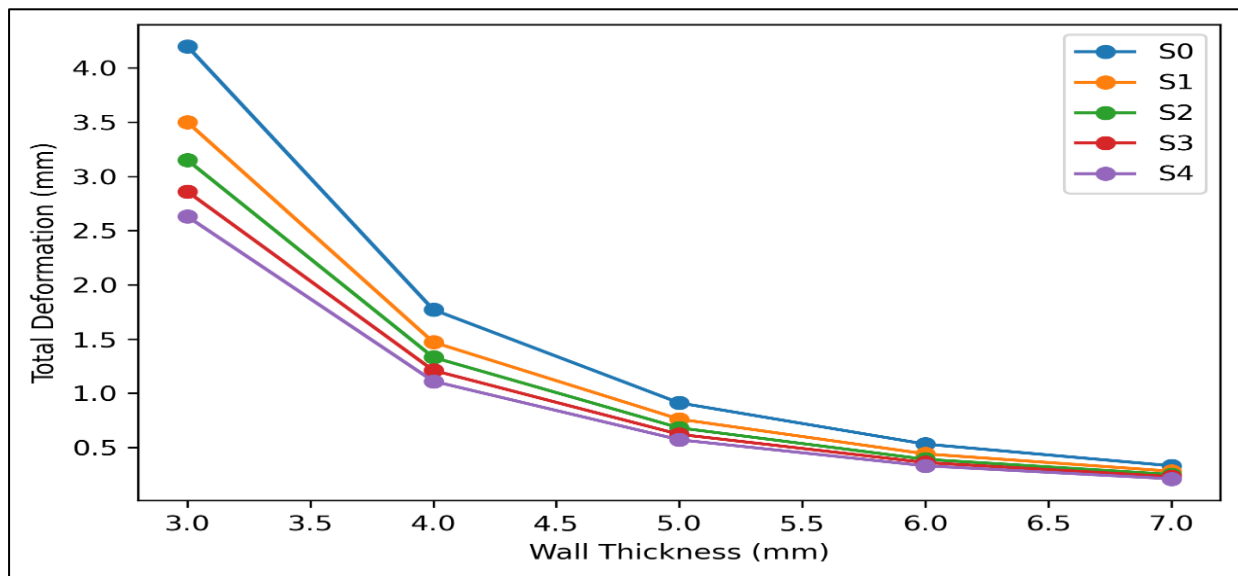


Fig 3 Total Deformation vs. Wall Thickness

Figure 3 presents the relationship between total deformation and wall thickness. The total deformation decreases with increase in wall thickness for composition and decreases with increasing fibre content at any fixed thickness. For the epoxy control (S0), deformation decrease from 4.20mm at 3mm wall thickness to about 0.33mm at 7mm, representing a 92% reduction. At 3mm wall thickness, deformation falls from 4.20mm (S0) to 2.63mm (S4) as fibre content rises from 0 to 40 wt%. The rate at which deformation decreases with wall thickness is non-linear, with the largest drop occurring between 3mm and 4mm, a diminishing return pattern at higher thickness.

The nonlinear drop in deformation with thickness can be explained by the bending mechanics of shell in which the flexural stiffness is proportional to the cube of all the wall

thickness. This causes a small increase in thickness to produce a large increase in stiffness and corresponding drop in deflection. This account for the pronounced curvature of the plot and the diminishing effect of further increase beyond 5-6mm. This reduction in deformation with increasing fibre content indicates the reinforcing effect of the banana fibre on the elastic modulus of the composite. The deformation value obtained in this study fall within a range generally considered acceptable for a socket of this size, indicating that a wall thickness of 4-5mm, combined with a fibre content in the range of 20 -30w%, offers a good balance between comfort, structural performance and thickness.

➤ *Effect of Wall thickness and Fibre Composition on Equivalent Strain*

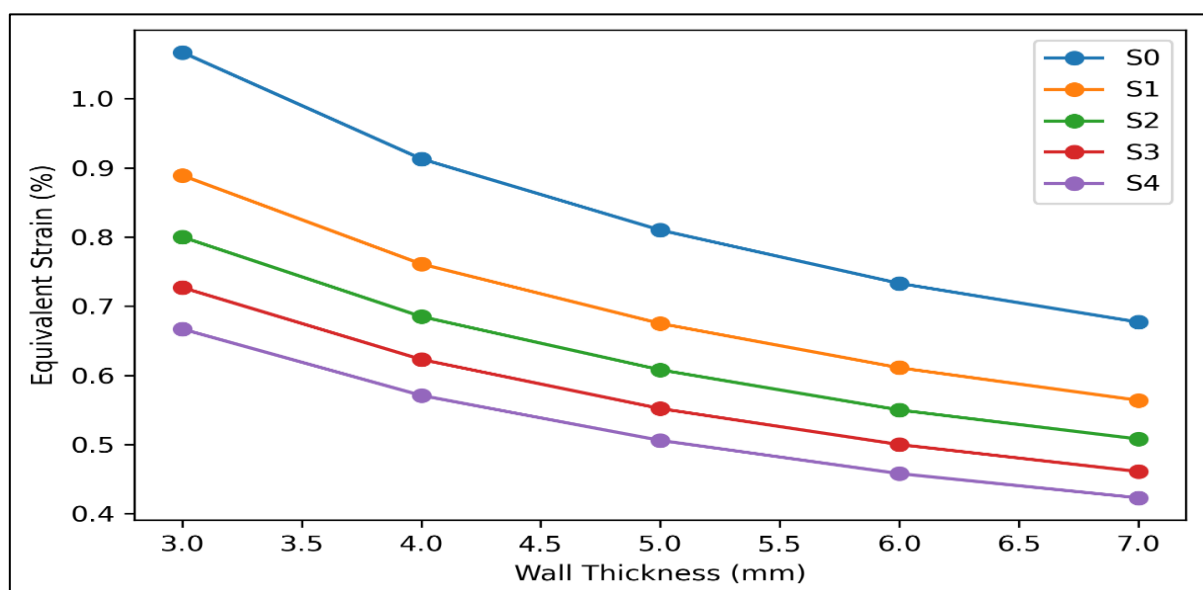


Fig 4 Strain vs. Wall Thickness

Figure 4 depicts the relationship between wall thickness and fibre composition on Equivalent strain in percentage. It is observed that equivalent strain decreases as wall thickness increases across all compositions. Equivalent strains in percentage ranges from a maximum of 1.06% (S0, 3mm) to a minimum of 0.423% (S4, 7mm). This behaviour stems from the linear elastic relationship between stress, strain and modulus of Elasticity. Since strain is the ratio of stress to modulus of elasticity, both effects act in the same direction, thus reduced stress and increased stiffness compounds to produce a steep reduction in the strains observed from (S0, 3mm - to S4, 7mm).

These findings, is consistent with studies in fibre reinforced polymer composites where increasing reinforcement content increase the modulus of elasticity and reduces deformation under equivalent applied stress because the stiffer fibre phase contributes more effectively to load transfer within the structure of the composite [18]. Also, trends have been reported in studies for banana fibre reinforced epoxy composites where increasing fibre fraction

improved stiffness related mechanical properties until limitations associated with fibre wetting, inter facial bounding and dispersion became dominant. This present study contributes to this body of knowledge by demonstrating the effect of fibre reinforcement on deformation behaviour of a prosthetic socket geometry evaluated through finite element analysis.

All strain value remains below a typical elongation at break of a comparable treated natural fibre epoxy composite. This indicates that the socket operates comfortably within its elastic region across the 25-case design space, hence not at risk of yielding at the ultimate load condition. This will reduce risk of cumulative fatigue damage on repeated loading and unloading cycles experienced during normal daily gait. This is an important durability feature required for prosthetics devices expected to withstand years of continuous use.

➤ Effect of Wall Thickness and Fibre Composition on Factors of Safety

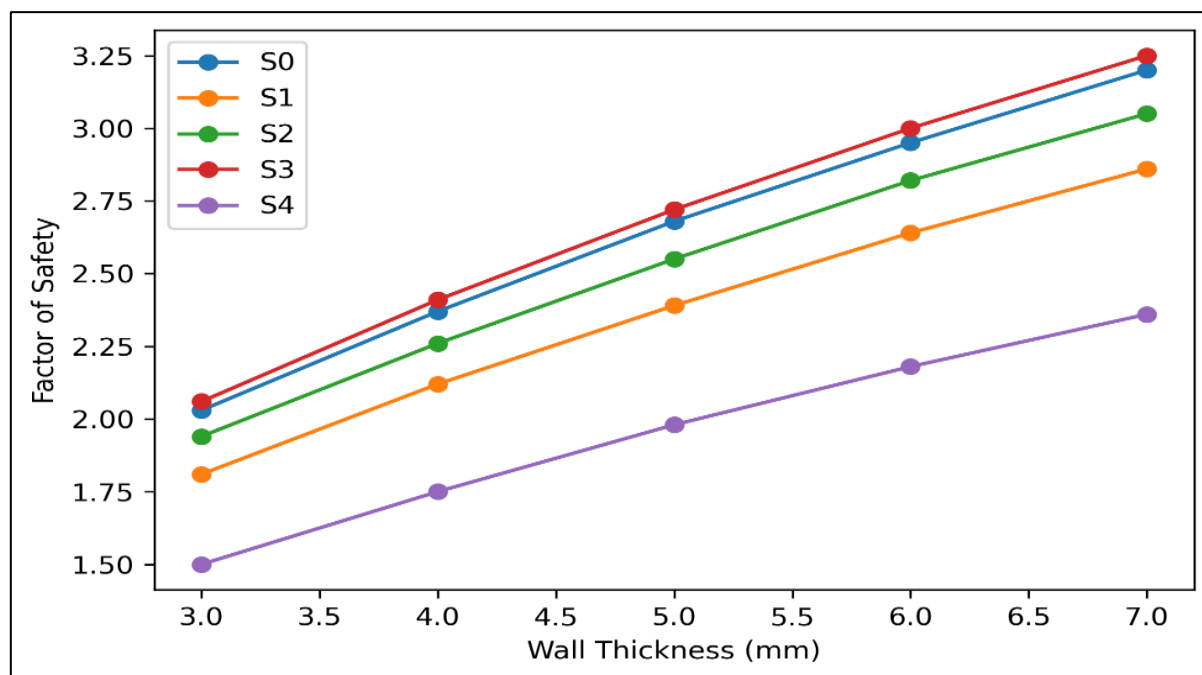


Fig 5 Factor of Safety vs. Wall Thickness

Figure 5 shows the relationship between wall thickness and fibre composition on factor of safety. As observed from the results, FOS increases as wall thickness increases for every composition, rising from about 1.5 -2.1 at 3mm to about 2.4 - 3.3 at 7mm. It can be observed that at a wall thickness of 3mm, FOS reduces from 2.06 at S3 to 1.50 at S4, which is the lowest value recorded across the entire 25 case matrix. It has been established in this study that the applied stress at each thickness is identical across all compositions, therefore, the difference in FOS across S0 - S4 arises from a change in the effective strength of the composite and not from the stress aspect of the factor of safety ratio. The improvement from (S0 to S3) is consistent with a better but progressive load transfer between the banana fibre and the matrix of the epoxy as the fibre content increases, up to an optimal loading level. The

significant decline at S4 (40 wt%) is explained by fibre loading effects as beyond an optimal weight fraction, fibre begin to agglomerate and are less uniformly wetted by the resin during hand lay-up, thus increasing stress concentration, trapped air and fibre to fibre contact points. This reduces the strength of the composite, even though its stiffness continuous to improve.

This behaviour is consistent with observations reported in studies for natural fibre reinforced epoxy composites, where mechanical performance often increases with fibre addition up to an optimum reinforcement level before declining due to increased formation of void, inadequate impregnation of matrix, agglomeration of fibre and reduced interfacial stress transfer efficiency[18].[19] in their study on

alkali treated natural fibre reported that excessive chemical treatment may reduce fibre integrity despite initial improvements in surface modification and crystallinity. Therefore, the reduction in strength observed in this study at 40wt% fibre loading is consistent with the established behaviour of natural fibre composites, where excessive reinforcement can improve stiffness while simultaneously reducing strength related properties due to processing - induced defects and weakness of stress transfer. This result has direct significance for the study's aim of selecting the best

composition thickness combination. The results indicate that S3 (30wt% banana fibre) combined with a wall thickness of 5mm provided the best balance, delivering a FOS values of 2.72 and above. In contrast, the 40 wt% composition (S4), despite its favourable stiffness, should be avoided in the final design of the socket. This is because it offers the lowest safety margin across the entire test matrix.

➤ *Von Misses Stress under Ultimate and Serviceability Load Cases.*

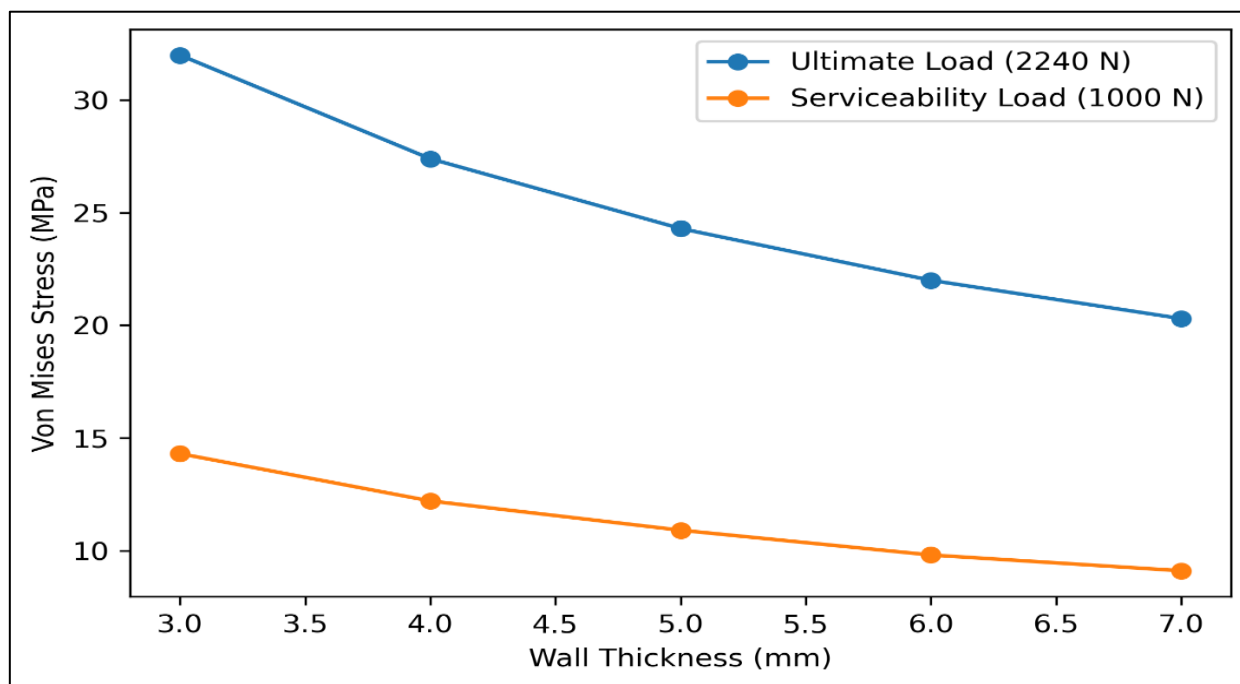


Fig 6 Von Misses vs. Wall Thickness under Ultimate and Serviceability Load Cases

Figure 6 shows the relationship between Von Misses stress and wall thickness under ultimate and serviceability load cases. The ultimate load case (2240N) against the serviceability load case (1000N) is shown. An identical decreasing trend shape with increasing thickness is followed by both curves, although the serviceability curve lies uniformly below the ultimate curve at every thickness. The serviceability values consistently equal to approximately 44.6% of the corresponding ultimate values (32.0 Mpa vs 14.3Mpa at 3mm and 20.3Mpa vs 9.1Mpa at 7mm)

This behaviour is explained by the linear elastic material model which is adopted for the finite element analysis in this study. Stress scales linearly with load under linear elasticity since the socket geometry material properties, boundary conditions and mesh are unchanged between the two load cases while the magnitude of the applied load differs. The ratio between the two magnitude (1000N / 2240N) is precisely reproduced in the ratio of the resulting strains, deformations and stresses. This confirms the internal consistency and correctness of the solved FEA model, rather than representing an independently derived result.

This proportional and multi case verification is consistent with established finite element modelling practice in prosthetic biomechanics where studies evaluate socket

performance under different gait phase and loading condition to characterize stress distribution, interface pressure and structural integrity [15]. Practically, the socket possesses a substantial structural margin under both extreme and routine loading conditions. At the serviceability load, which represents the normal daily use, peak stress (14.3Mpa at 3mm) is below the ultimate strength (48Mpa) of the composites, while the ultimate load case (32.0Mpa at 3mm) retains an adequate margin. This dual verification confirms that the socket developed in this study can comfortably support everyday use. This is essential evidence supporting the use of banana fibre epoxy socket design as a good fit for both comfortable daily wear and safety critical performance under high load scenarios such as misstep or stumbling.

➤ *Elemental composition of Banana Fibre*

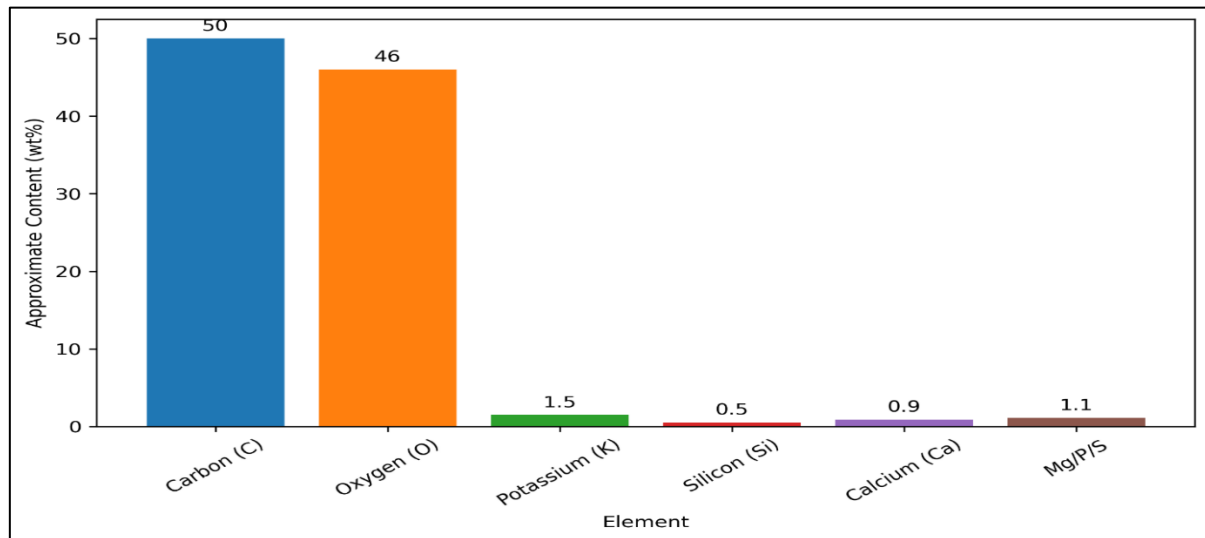


Fig 7 Elemental Composition of Banana Fibre

Figure 7 illustrates the elemental composition of banana fibre. The results indicate that the alkali treated banana fibre is composed of 50wt% carbon and 46wt% oxygen which account for 96wt% of the fibre's elemental mass. The remaining fraction consists of minor inorganic elements such as potassium (1.5%), silicon (0.5%), calcium (0.09%) while magnesium, Sulphur and phosphorus are present at less than 1% each. The dominance of carbon and oxygen is consistent with the lignocellulosic nature of plant fibre which is composed largely of cellulose, hemicellulose and lignin, a polysaccharide and phenolic polymers, built from repeating carbon - oxygen rich structure units. The small residual amount of calcium, potassium and other trace elements represents the natural mineral content of plant biomass. Their comparatively low levels indicate that the 5% (w/v) NaOH alkali treatment was effective in stripping away waxes,

surface impurities and some cellulosic material from the raw fibers.

The elemental profile obtained in this study is consistent with previous elemental characterisation studies of alkali treated fibre. Alkali treatment is widely reported in the studies of [19] to remove non - cellulosic constituent including hemicellulose, lignin, waxes and surface impurities. This results in increased Cellulose exposure. This elemental result helps to explain the composition dependent improvement and confirms that the specific alkali treatment adopted for this study was appropriate for preparing banana fibre for this epoxy composite application.

➤ *Mechanical Properties Used as FEA Input*

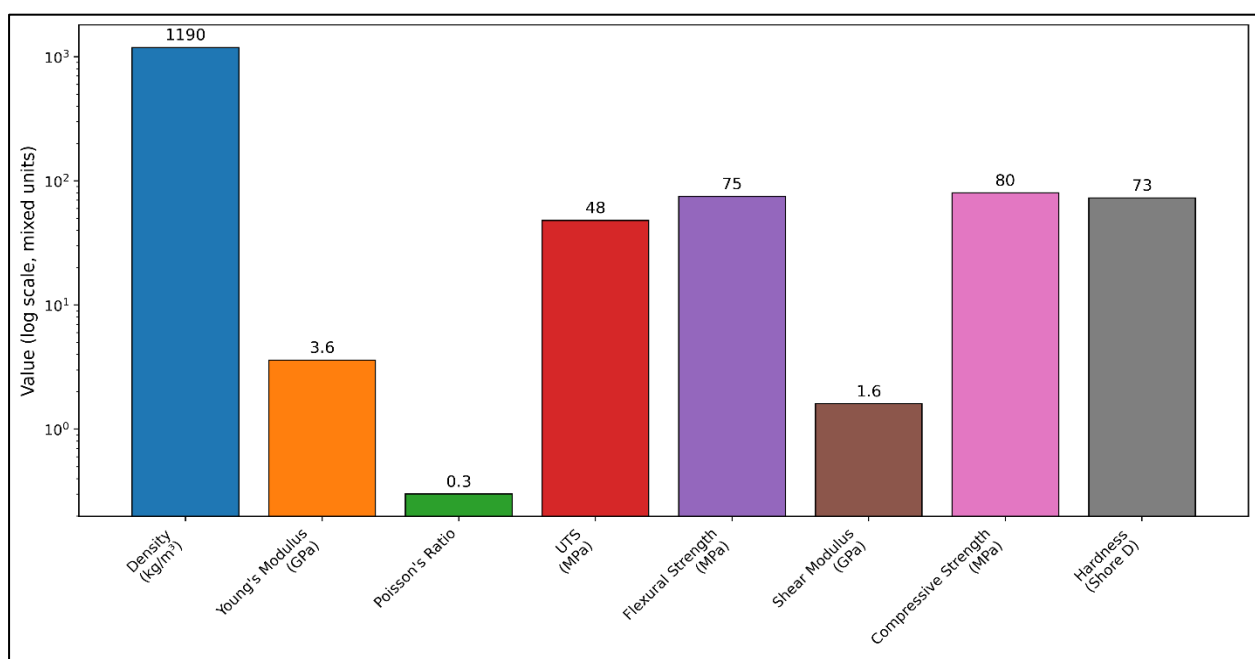


Fig 8 Mechanical Properties Used as FEA Input

Figure 8 summaries the measured mechanical properties used to define the composite's model in ANSYS. The properties are Young's modulus (3.6 Gpa) density (1190kg/m³) poisson's ration (0.3), Flexural strength (75Mpa), ultimate tensile strength (48mpa), compressive strength (80 Mpa) and shore D hardness (73). It was observed from the result that Flexural strength and compressive strength both exceed the ultimate tensile strength while the shear modulus value reported is significantly lower in magnitude compared to the value of Young's modulus. The high value of the flexural strength as compared to the tensile strength is a commonly observed feature of fibre reinforced polymer composites, undergoing three point bending test, where only the outer fibres reach peak stress, while the flexural strength calculated is obtained from beam theory, rather than uniform axial stress, thus yielding a value higher than pure tensile strength. Similarly, compressive strength exceeding tensile strength is common in fibre composites because the two loading modes are governed by different failure mechanisms. Compressive failure is governed by fibre-micro buckling, cracking or matrix yielding while tensile failure is controlled by fibre matrix debonding and pull out, or fibre fracture.

The tensile and flexural strength values obtained in this are study are comparable with and in several cases higher than, those reported for alkali-treated banana fibre reinforced epoxy composites in previous studies. This present study achieved a tensile and flexural strength of 48Mpa and 75Mpa respectively. This indicate improved load transfer efficiency between the banana fibre and epoxy matrix. This enhanced mechanical response is attributed to the combined effects of alkali treatment which help in the removal of non - cellulosic component and improves fibre surface adhesion. Similar studies have that appropriate chemical modification and fibre concentration can improve interfacial bounding and transfer of stress, whereas excessive fibre content will result in fibre agglomeration, reduced mechanical performances and poor wetting [18,19]. Therefore, the higher strength values observed in this present study suggested that the selected fibre proportion, treatment condition and composite processing approach provided favourable inter facial interaction and structural performances. The accuracy of the mechanical input result is central to the credibility of the simulation results. Their comparison to literature provided evidence, lends confidence that the characterisation and mechanical testing produced is genuinely well-bound and improved composite. This supports the conclusion that banana fibre reinforced epoxy is mechanically viable and sustainable materials for below knee prosthetic socket fabrication.

IV. CONCLUSION

The study demonstrated that alkali- treated banana pseudo stem fibre reinforced epoxy composites are mechanically sustainable and viable candidate materials for below - knee prosthetic socket fabrication. Through a combined experimental and computational method, FTIR, EDXRF and XRD confirmed effective removal of non-cellulosic impurities following alkali treatment, while mechanical characterisation yielded input properties that compared favourably with, and in several cases exceeded

values reported for similar banana fibre composites. FEA carried out across a full factorial design of 25 cases under ISO10328 ultimate and serviceability loading indicate that Von Misses stress and deformation both decrease with increasing wall thickness. It was observed that deformation reduces at higher fibre content and factor of safety improves progressively with fibre loading up to 30wt% before declining at 40wt% due to fibre agglomeration and reduced interfacial load transfer. All 25 simulated configuration remained structurally safe under the applied ultimate load condition, but the 30wt% fibre composition combined with a 5mm wall thickness was identified as the optimal configuration as it offered the best balance of deformation, stress, stiffness and wearable mass. These finding indicate that banana fibre, an abundantly and largely under-utilised agricultural byproduct can be engineered into a structurally low cost, sound and environmentally sustainable alternative to imported carbon and thermoplastic socket materials. This offers a practical pathway to improving the accessibility of prosthetic devices in Nigeria and other resource constrained settings.

LIMITATION OF THE STUDY

The study's limitation stem primarily from the simplification of the FEA model. The socket geometry was an idealised TSB profile rather than a patient specific 3D scan, hence anatomical variation and residual limb shape were not captured and no residual limb surface interface was modelled. The composite material was treated as Isotropic homogeneous and linear elastic which ignore randomly oriented discontinuous nature of the actual lay-up material. The loading was assumed to be static and the FEA predictions were not validated experimentally against a physical prototype.

RECOMMENDATIONS FOR FURTHER STUDY

Future work should build on this study by moving toward greater realistic experiment and validation. This includes developing a patient specific socket models from 3D scanned residual limb geometries to assess anatomical variability affects the composition thickness relationship reported in this study. On the modeling side, further studies should incorporate the anisotropic and micro mechanical material properties which would better capture the composite's directional behaviour than the one used in this study. Future analysis should be extended to dynamic and fatigue loading as this will help evaluate long term durability and service life under repeated gait cycle. Finally, a life cycle assessment and cost comparison between conventional thermoplastic or carbon fibre sockets should be carried out to quantify the economics and sustainability benefits claims for the banana fibre composite approach of this study.

➤ CRediT Authorship Contribution Statement

Sifon J. Umoh - Writing original draft, Conceptualization/supervising, Analysis of results/writing; Kufre E. Jack – Review and Editing; Williams A. Onuh – Laboratory work/Methodology; Ephraim R. Afia - Review

and Editing; Akanimo U. Ekpeyong - Analysis of results/Writing.

➤ *Declaration of Competing Interest*

The authors declare that they have no known financial competing interest or personal relationship that could have appeared to influence the output of this study.

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