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The Influence of Various Fiber Reinforcements on the Performance of Transtibial Prosthetic Socket

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Abstract

Bamboo and other plant-based Fibers have become more popular in material science. This work involves the fabrication of a composite prosthetic socket by combining polymethyl methacrylate 80:20 with natural and synthetic Fibers. Hybrid laminated composite materials for transtibial prosthetic sockets are produced through vacuum casting and classified into three groups. These groups incorporate different combinations of bamboo, Kevlar, UHMWPE, and glass Fibers. This study confirms the experimental results for specific Fiber volume fractions using numerical finite element analyses by using ANSYS-22. Results show that the mechanical and physical properties are substantially influenced by the type and amount of reinforcing Fiber layers. Laminates comprising four layers of bamboo Fiber plus two layers of Kevlar Fiber demonstrated the highest ultimate tensile strength (UTS) values at 179 MPa. Hybrid laminates consisting of 4 layers of bamboo plus 2 layers of UHMWPE and 4 layers of bamboo plus 2 layers of glass exhibited ultimate tensile strength (UTS) values of 128 MPa and 89 MPa, respectively. The research indicates that bio composites perform best when using a proper blend of natural and synthetic reinforcing Fibers. The safety factor investigation indicates that all the laminated composite samples, including those with varying lamination distributions, possess a minimum safety factor of 3.06 for the below-knee socket, which appears safe and satisfactory. This study comprehensively investigates the benefits of various amounts of synthetic Fibers and natural Fiber lamination layups for enhancing the strength of PMMA resin composites. It gives us new information about a topic that hasn't been looked into before.

Introduction:

Prostheses are used to compensate for the functional loss of upper or lower limbs as a result of amputation. The socket is an important prosthesis component because it interfaces the human stump and other prosthetic components. The socket's form and fit are adapted to human factors, considering comfort, energy consumption, and general acceptability. The efficacy of the socket in providing efficient load transfer and weight-bearing across various parts of the prosthesis is vital for the success of a prosthesis [1]. Amputees often have higher energy requirements than non-amputees. The energy demands tend to rise in direct proportion to the extent of amputation, especially in situations with more extensive amputations [2].

Pineapple, bamboo, banana, sisal, henequen, jute, ramie, coconut (coir), rice husk, wood, and wheat straw are being investigated as reinforcing materials in polymer matrices. Composite reinforcements made from lignocellulosic plant fibers have several benefits over mineral fillers. These thin fibers have excellent elasticity modulus and specific strength. They are smooth and safe for composites. All lignocellulosic natural fibers have cellulose microfibrils in an amorphous lignin and hemicellulose matrix, like ramie fibers [3]. Bamboo, which comprises about half of the world's bamboo forests and grows mostly in Southeast Asia, is underutilized. This substance helps preserving ecological equilibrium and socioeconomic growth. The current work employed bamboo and ramie fibers, usually used for weaving, to reinforce a polypropylene composite like glass and carbon fibers.

Researchers created a below-knee socket using suction. The research examined how fiber layering sequence affected socket mechanical and volumetric features [4,5]. To obtain excellent prosthetic sockets, interface pressure and residual limb stresses must be uniformly distributed in all directions. Even distribution is vital for wearing and doffing, decreasing fatigue and discomfort. Dual-wall sockets are ideal for sensitive skin locations such as the fibular and distal tibia. The outer layer is hard, and the inner layer is semi-flexible, making this design lightweight and comfortable [5]. Composites have transformed orthopaedic and prosthetic device manufacturing. Fiber is an important multiphase resource in orthopaedics, specially reinforced polymer composites. Carbon fibre's tension and compression rigidity make it the most desirable reinforcement. Perlon fibers, carbon fabric, and PMMA polymer resin, used in socket manufacture, are sustainability problems and may produce toxic gasses and dust, requiring costly safety equipment. Natural fibers are inexpensive and recyclable [7].

Noor K. Faheed et al. in [8]. Natural fibers are suggested as a substitute for the materials commonly used in making below-the-knee prosthetic sockets. The researchers concentrated on fabricating a prosthetic socket by enhancing a composite material with natural fibers. According to the study, natural fibre-reinforced composites have the potential to be used instead of traditional materials in making prosthetic sockets for below-the-knee amputees. J.K. Oleiwi [9] and colleagues researched natural fiber-reinforced composites. They investigated how the composites' behaviour altered based on the number of jute fiber layers and their orientations (45° and 0°/90°). The research concentrated on mechanical and physical aspects like density and hot disk performance. The findings revealed that the mechanical characteristics of the composites improved as the number of layers of jute reinforcement increased. The tensile load behaviour was modified by the fiber direction (0°/90°). A. S. Abbas and S. D. Dawood [10] researched the utilization of numerous layers of different prosthetic materials and the chemical processes that occur when the lamination resin blends. The research by D. Widhata et al. [11] investigated the effects of replacing socket prosthesis materials with methyl methacrylate polyester resin and water hyacinth fiber composites. The research tested these composites' mechanical characteristics using tensile and bending tests. The resin and water hyacinth fiber composite socket performed well and might replace the usual arrangement.

The study aimed to determine the optimal method for constructing composite materials for lower-limb prosthetic sockets. We determined the safety factor by doing tensile tests to evaluate mechanical properties using AutoCAD and ANSYS 22 for calculations. The numerical methodology was then compared to the conventional vacuum molding process to determine the most efficient way of producing lower limb sockets. The aim was to improve the manufacturing process of prosthetic sockets by considering both mechanical qualities and safety aspects.

Experimental procedures used in this research.

This article will explore the process of manufacturing sockets, which involves selecting appropriate materials, using certain equipment and meticulous preparatory phases to achieve the desired mechanical properties. Additionally, we provided information on the mechanical tests that may be used to evaluate the performance of the socket.

Material used in this study:

The materials used for testing the lamination of the below-knee socket in this study consist of UHMWPE and Kavler fibres (produced by B-CHEM company), a woven mat of bamboo fiber produced by Changzhou Doris Textile Co., Ltd, glass fiber (produced by Ottobock company), and Perlon stockinet (item name 623T5 from Ottobock company). In addition, crucial components for prosthetic sockets include hardening powder, polyvinyl alcohol (PVA) bag, and Jepson for the casting process.

This Study's Instrumentation:

Research tools in this case include.

- The Jepson mould is rectangular and 27 cm long, 18 cm wide and 10 cm high.
- A vacuum system with a pump and supports is intended to keep the Jepson pipes firmly in place.
- A mechanical workshop has a range of tools built particularly for shaping and cutting materials using a CNC machine.
- Test metric universal instrument machine test.

Procedure of Sample Manufacturing:

Table 1. presents a list of different laminated composite materials used for this work.

Lamination	Sum of Layers	No. of Lamination
Group A	10	(2Perlon+2Bamboo+ 2Kavlar +2Bamboo+ 2Perlon)
Group B	10	(2Perlon +2 Bamboo + 2 UHMWPE +2 Bamboo +2Perlon)
Group C	10	(2Perlon +2 Bamboo + 2Glass +2 Bamboo +2Perlon)

The production process for the samples entailed multiple steps. Firstly, a gypsum mould was created and connected to a vacuum system via pressure tubes. Then, the inner layer of the PVA bag was placed onto the gypsum moulds, and the vacuum system was used to apply suction, avoiding bubble formation and bonding between the resin and gypsum mould. The lamination lay-up added bamboo, glass, Kavler, UHMWPE fibers and perlon stockinet, as presented in Table 1 and illustrated in Fig. 1a and c.

Following this, an external layer of PVA was applied, and then a length of cotton thread was used to fix the PVC bag, keeping the smaller tip on the valve. A vacuum system was utilized to suck out the air between all the bags, leaving the top end open for resin supply. The polymethyl methacrylate resin was mixed with the hardener according to the standard ratio of 2-3, and the resulting mixture was then placed inside the external polyvinyl alcohol bag (PVA), where the matrix was distributed uniformly over the area of lamination stockinet, as depicted in Fig.1 d. The vacuum device was left running until the composite material solidified, after which the resulting lamination was removed from the gypsum mould. As demonstrated in Table 1, three different types of laminated composite materials were produced.

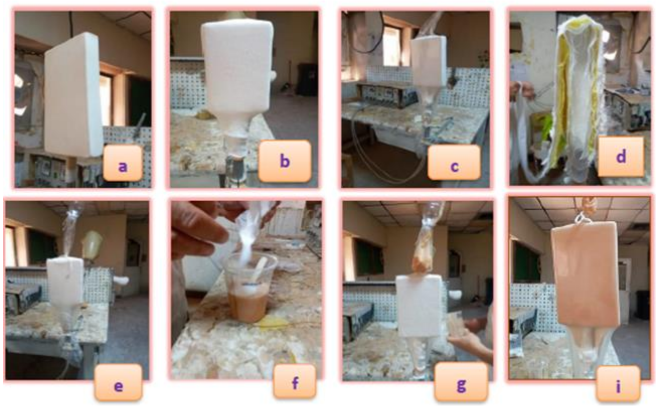


Fig.1*: Demonstration of the process of preparing test specimens for a below-knee prosthetic socket and various steps involved in the preparation procedure.*

Testing for Modified Laminated Composite

Tensile Test.

Tensile tests were done on the laminated composite samples to determine their mechanical properties. This involved creating a stress-strain curve for each sample. For making tensile laminated composite specimens, the ASTM standard (D638-14 Type I) is used as a guide [13]. The tensile test was done with a 5 mm/min feeding speed on an Instron universal testing machine until the specimen broke under load. The stress-strain curve was used to determine the modulus of elasticity, the ultimate tensile strength and the amount of the laminate stretched before breaking [19-22]. The instruments, a conventional tensile test sample, and the samples before and after testing are shown in Fig.2.[23]

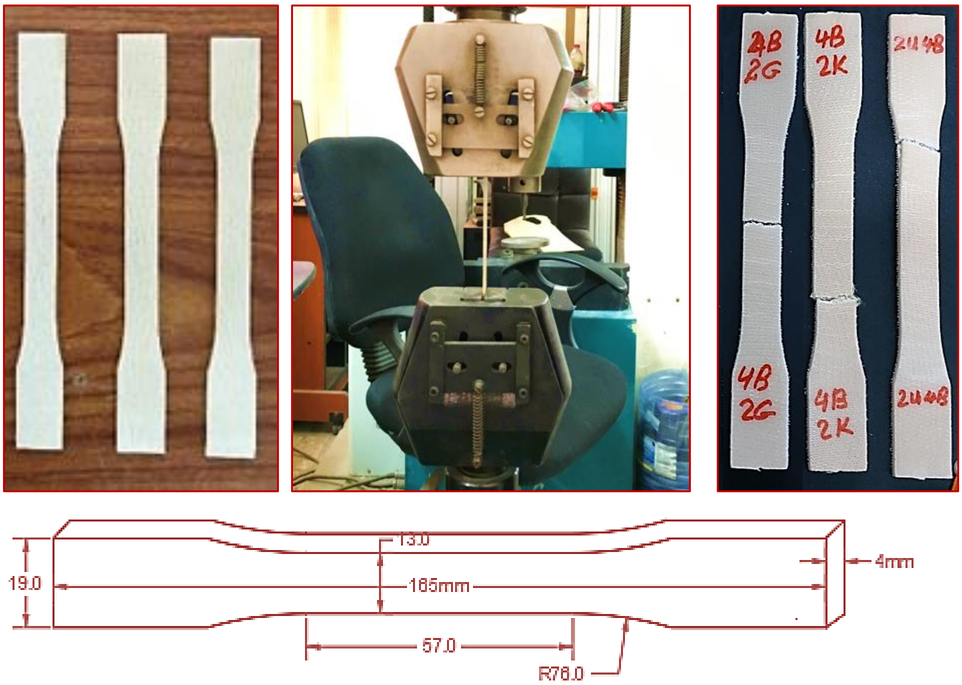


Fig. 2: *(a) The samples before tensile testing, (b) Testing apparatus, (c) The samples after tensile testing and (d) The standard sample dimensions.*

Numerical Results of a Modified Laminate Composite.

To analyse the motion system of patients, a prosthetic socket was divided into four categories based on its weight-bearing properties (anterior, posterior, lateral, and medial), and interface pressures were measured between the below-knee socket and residual lower limb during self-selected walking speed [24]. A finite element approach (ANSYS-22) was used to simulate the socket and evaluate the von Mises (stress and strain) and total deformation by applying boundary conditions. This involved measuring the interface pressure distribution in various socket areas and fixing support at the tip of the socket's bottom. For the model to give complete results, the mechanical properties of prosthetic sockets of all groups of composite materials were added to the workbench ANSYS 22 data [25-27]. The finite element analysis was conducted using ANSYS Workbench 22 software on a prosthetic socket with a body mass of 76 kg [28]. The process was completed using automatic meshing, resulting in 9351 elements and 18606 nodes. The meshing process was accurate, and the interface pressure was properly located, as shown in Fig. 3. Table 2 summarizes the pressures on the socket plane, which were tested at the most dangerous point in the gait cycle when the heel hits the ground.

Table 2. presents the location and average pressure data at the heel strike site observed in the prosthetic socket. [29-31].

location	Anterior	Lateral	Posterior	Medial
Interface pressure (MPa)	105	70	95	85

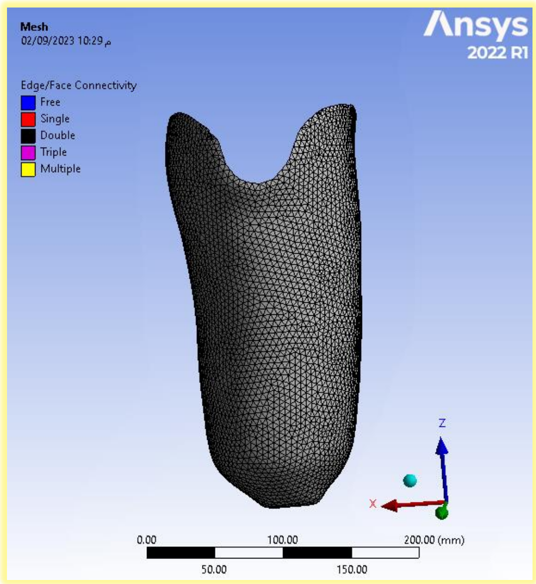


Fig. 3: *Process of meshing sockets.*

Experimental Result for Modified Laminated Composite

Results of tension testing on modified laminated composites:

The tension test results in this study gave important information about the tensile properties of lower limb below-knee composite prosthetic sockets, such as their modulus of elasticity, ultimate tensile strength, and elongation at break. The study found that the type of reinforcement used had a big effect on the tensile properties. This shows the importance of choosing the right reinforcement material to get the best tensile strength in the composite.

Tensile strength for modified laminated composite:

The results show that the ultimate tensile strength (UTS) values vary depending on the reinforcing fibers used. Adding four layers of stabilized bamboo fibers to different synthetic fibers (UHMWPE, Kevlar, and glass) fibers significantly affect composite materials' ultimate tensile strength (UTS) values for constructing prosthetic limb sockets. This implies that incorporating more fibre layers can improve the laminated material's ultimate tensile strength (UTS). The different levels of ultimate tensile strength come from the different qualities of bamboo, Kevlar, UHMWPE and glass fibers. Fig. 4 shows that the laminates, including four layers of bamboo fibre and two layers of Kevlar fibre, had the greatest UTS values, followed by hybrid lamination (4 bamboo + 2 UHMWPE) and the hybrid lamination (4bamboo + 2glass), with values of 179Mpa, 128Mpa, and 89Mpa, respectively. This is because, with Kevlar fibers included, stresses could be transferred more easily from the matrix to the fiber with the greatest ultimate tensile strength (UTS). This highlights the influence of reinforcing fibers on composite materials' durability and tensile strength this agreement with reference [32].

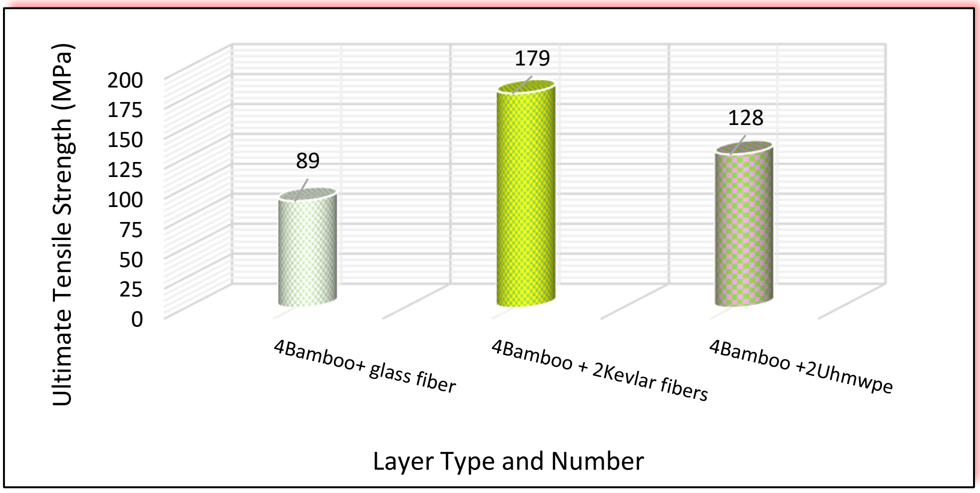


Fig. 4: *Influence of reinforced natural fibers (bamboo) plus synthetic fiber layers on ultimate tensile strength.*

Young's Modulus for modified laminated composite:

The modulus of elasticity measures the rigidity of a component. Fig.5 shows how the modulus of elasticity is affected by the amounts and type of reinforcement fiber layers, such as bamboo, Kevlar, UHMWPE and glass fibers, added to the Polymethyl methacrylate resin PMMA matrix. The results indicate that as the number of reinforcing layers increases, the elasticity modulus also increases. Adding two layers of glass fiber to four layers of bamboo fiber led to a gradual increase in the modulus of elasticity due to the rising binding forces from the increased layers of glass fiber. All three laminations, consisting of four layers of bamboo fiber and two layers of Kevlar, exhibited the highest modulus of elasticity among all the laminations tested because of how Kevlar fibers. These fibers do a good job of transferring loads from the matrix to the fiber, making the composite material stronger and stiffer. On the other hand, Young's modulus is 3.473 GPa for lamination (4 bamboo + 2 Kevlar) in agreement with reference [18].

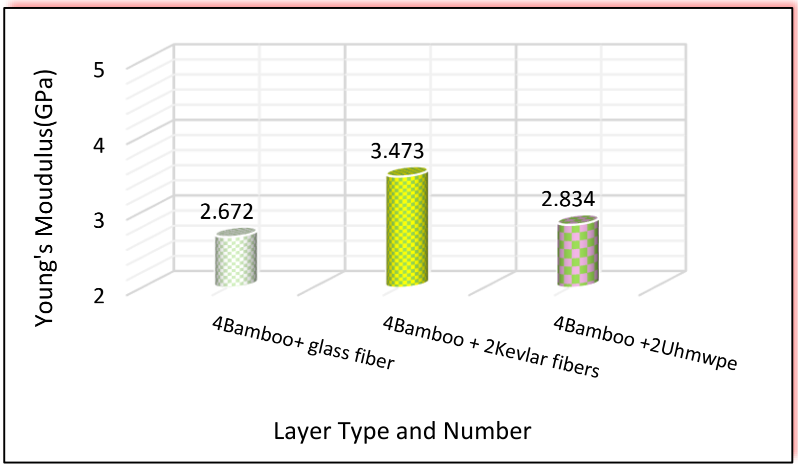


Fig.5*: Influence of reinforced natural fibers (bamboo) plus synthetic fiber layers on Young's modulus.*

Percentage of elongation for modified laminated composites:

To study how fiber content affects the elasticity of the polymeric matrix, we estimated the percentage of elongation-at-break value. The findings show that the elongation % is affected by the reinforcing fibres. Adding four layers of stabilized bamboo fibres and various kinds of synthetic fibres (Kevlar, glass, and UHMWPE fibers) significantly affect the elongation % of the composite materials before they break. Fig.6 demonstrates that the hybrid lamination (4 bamboo + 2 Kevlar) fibres had the least amount of elongation, followed by the hybrid lamination (4 bamboo + 2 UHMWPE) fibers, and lastly, the hybrid lamination (4bamboo + 2glass) fibres, in that order, with values of 5.61mm, 8.46mm, and 9.21mm. This indicates that glass fiber is more rigid than Kevlar fiber, but that rigidity also implies less durability because Kevlar fiber has a higher elongation-to-break. The elongation percentage decreases as the brittleness of the composite increases in agreement with reference [33].

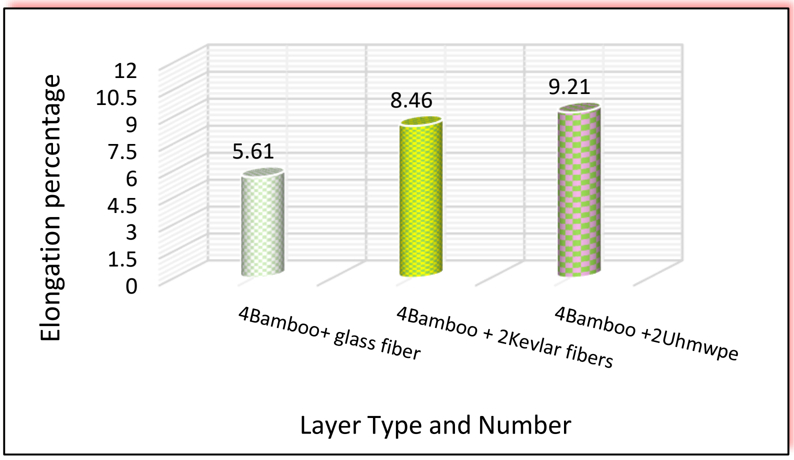


Fig.6: *Influence of reinforced natural fibers (bamboo) plus synthetic fiber layers on elongation percentage.*

Numerical Analysis for Modified Laminated Composite

Total deformation in modified laminated composites:

The deformation investigation revealed important information about the functioning and shape of the lower-limb prosthetic socket. For the tested model, lamination (2 Perlon layers + 2 bamboo layers+2 Glass layers +2 bamboo layers + 2 Perlon layers) had the maximum total deformation of 5.32 mm and lamination with (2 Perlon layers + 2 bamboo layers + 2 Kevlar layers + 2 bamboo layers + 2 Perlon layers). It had the lowest deformation at 4.098 mm, Fig.7 illustrates how the overall deformation of the below-knee socket varies as the types and number of reinforced fibres in each lamination increase. When these fibres are used, the total deformation values of the below-knee prosthetic socket are within an acceptable range. This is critical because the below-knee socket must flex within the prescribed range to suit the patient's comfort needs. Furthermore, Fig.8 shows that the deformation values are lowest in the socket's basal plane and largest in the lateral plane's centre in agreement with reference [34].

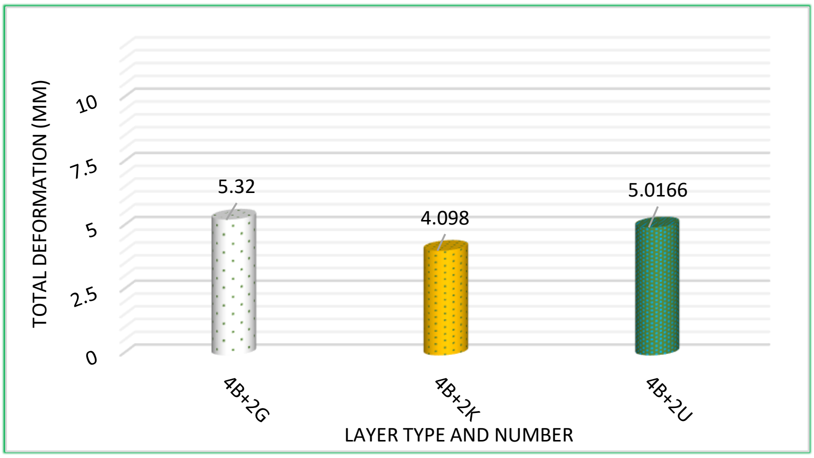


Fig.7: *The total deformation in lower limb prosthetic socket specimens for various lamination distributions.*

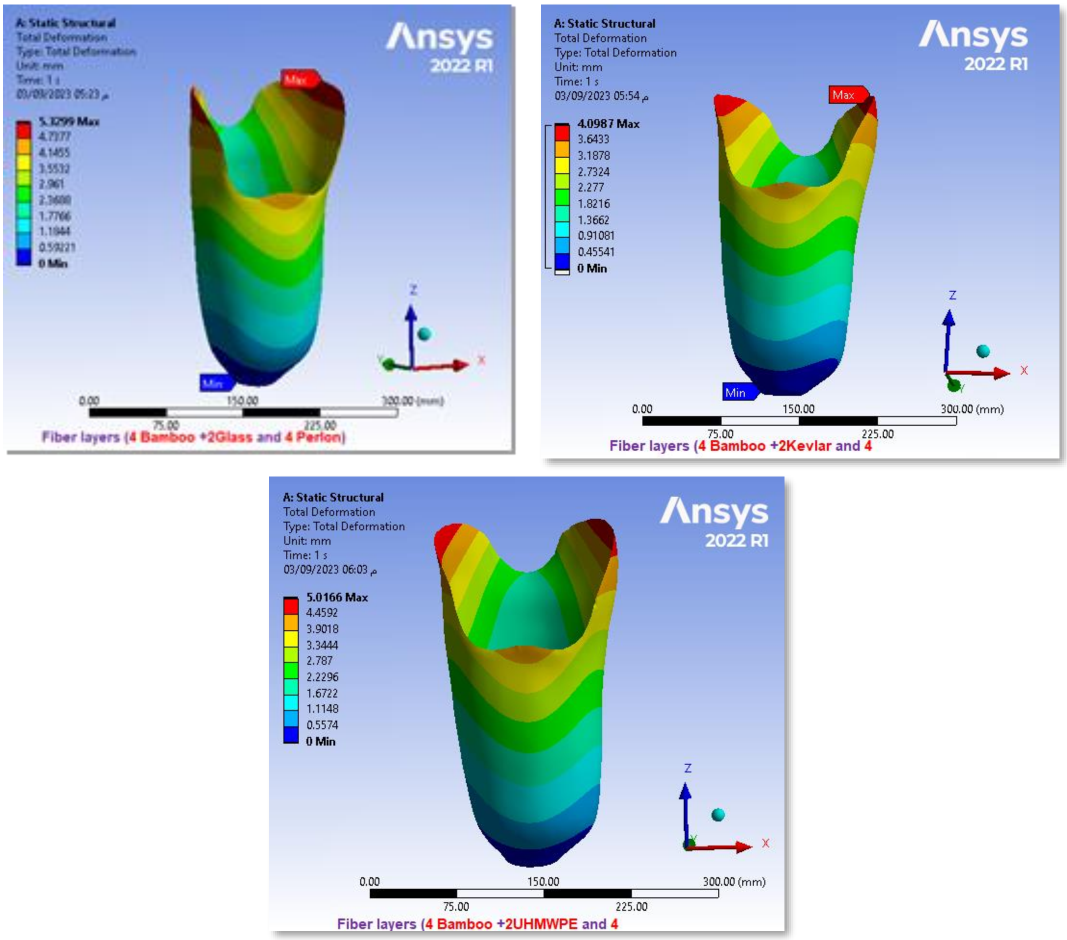


Fig.8: *Total deformation contours for a laminated composite with a different lamination distribution.*

Von-Mises strain evaluation for modified laminated composite

Based on Fig.9, the lower limb below the knee socket had the most strain in front of the tibia below the knee bone at the centre, where the value was 0. 0113. However, the pressure on the (posterior, medial, and lateral sides) was lower than on the front, especially with lamination ((2

Perlon layers + 2 bamboo layers+2 Kevlar layers +2 bamboo layers + 2 Perlon layers)). This difference may be because bamboo and Kevlar fibers have different mechanical properties this agreement with reference [18]. Fig.10 shows the shape of the equivalent elastic strain for all-laminated socket test samples used in this study.

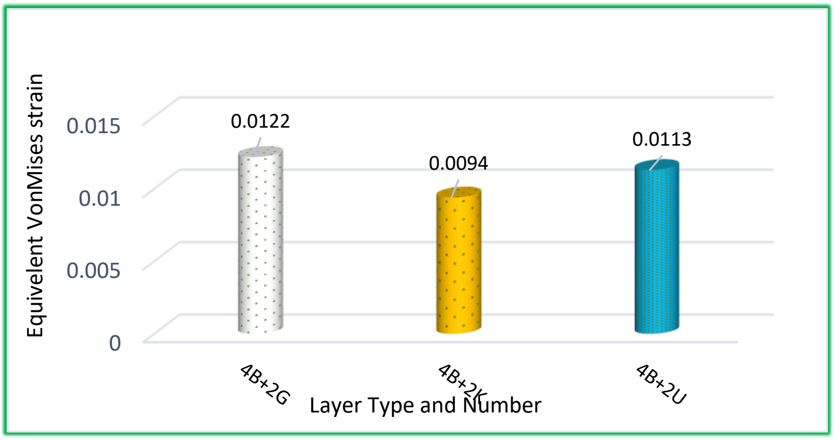


Fig.9: *Variation equivalent to Von-Mises strain for modified laminated composite*

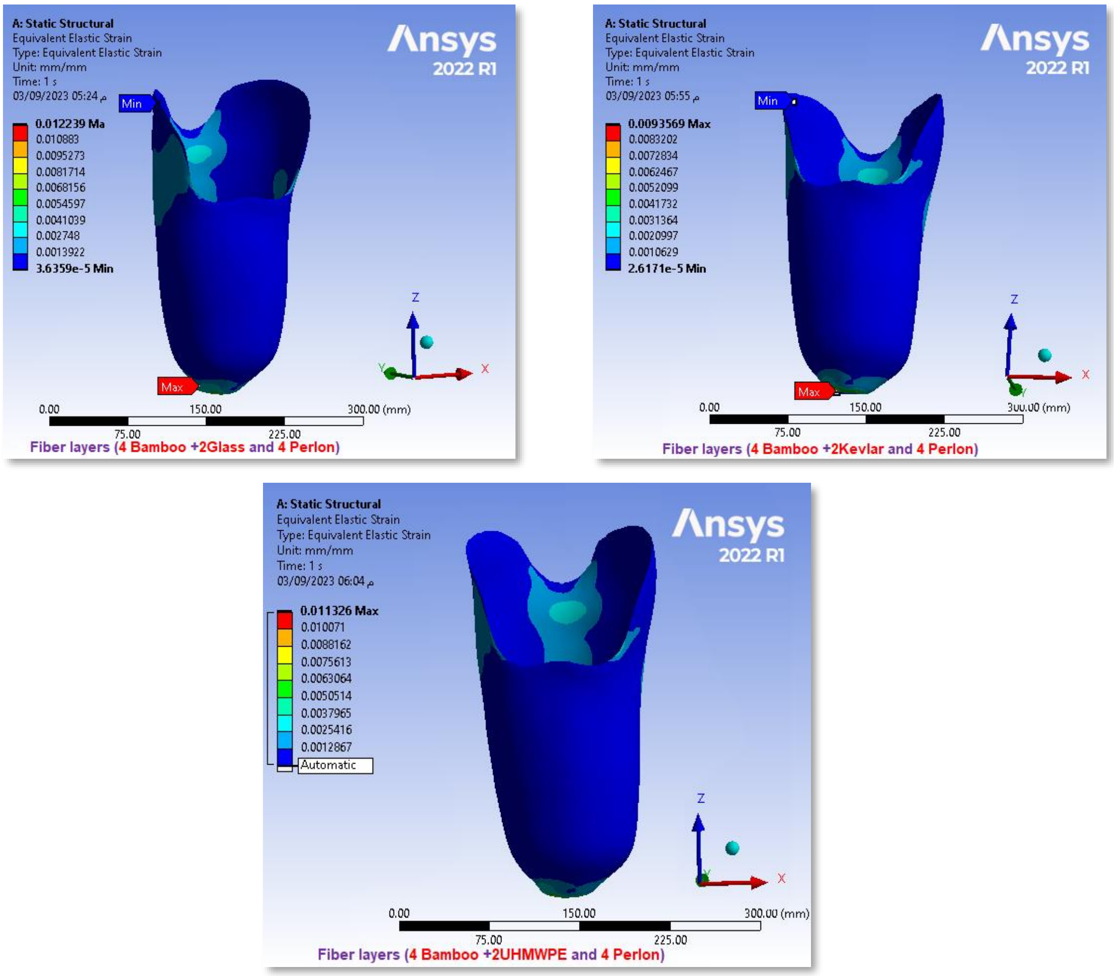


Fig.10: *Variation equivalent to Von-Mises strain for modified laminated composite.*

Von-Mises Stress analysis for modified laminated composite

Researchers conducted a numerical simulation on an adapted laminate composite to analyse the stress and deformation of a below-knee prosthetic socket. During walking gait cycles, the simulation focused on how the pressure was distributed between the rest of the leg below the knee, the inside of the prosthetic socket and the body mass. The study utilized an equivalent von Mises stress analysis to determine stress distribution within the prosthetic socket and the resulting deformation caused by the distributed pressure. Results showed that the highest stress occurred on the centre side of the anterior of the socket, specifically in the lamination (2 Perlon layers + 2 bamboo layers+2 Glass layers +2 bamboo layers + 2 Perlon layers), which produced a stress of 27.41 MPa. Meanwhile, the pressure on the lateral, medial, and posterior sides was lower than on the anterior side. Fig.11 presents the von Mises stress values for the total laminate samples tested. Fig.12 shows the composite designs and the overall variation of von Mises stresses throughout the prosthetic socket material. Additionally, the location and magnitude of von Mises stresses are displayed in Figure 16.

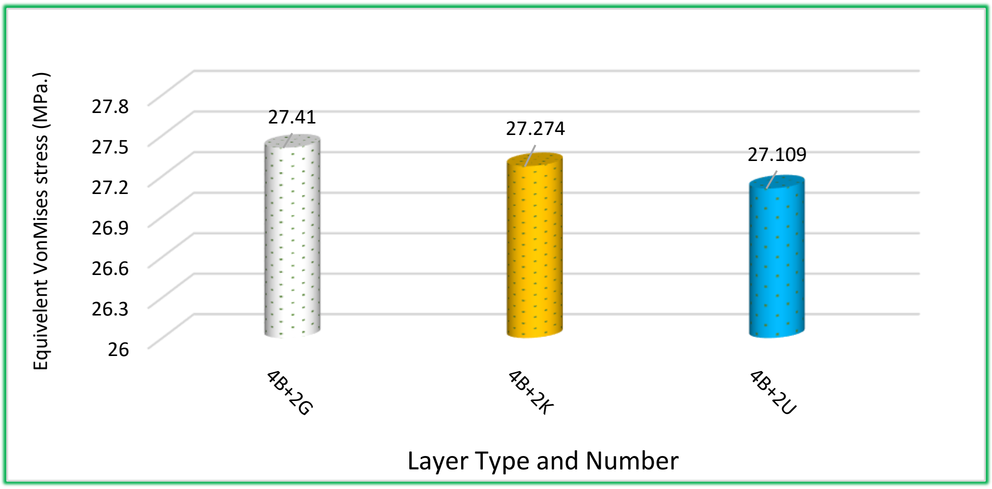
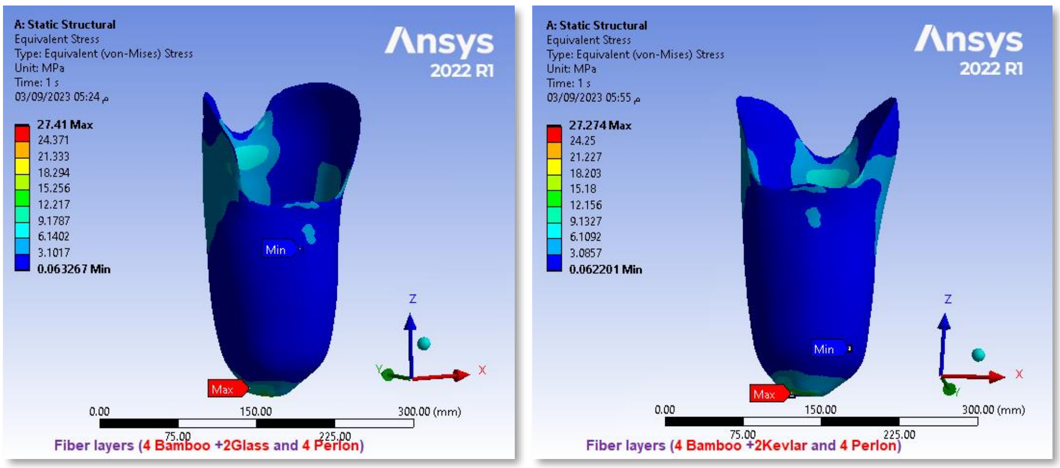


***Fig.11**: Variation equivalent to Von-Mises stress for modified laminated composite.*



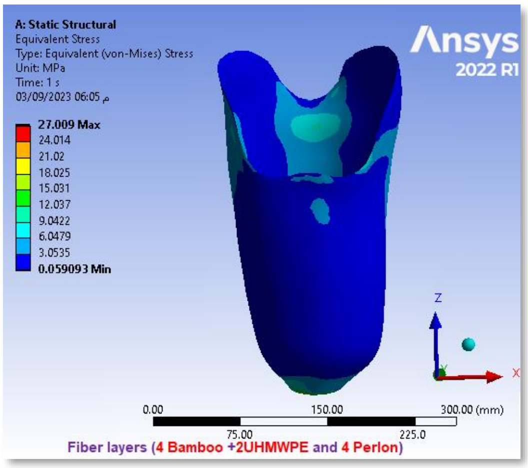


Fig.12: *Variation equivalent to Von-Mises stress for modified laminated composite.*

Safety Factors for Modified Laminated Composite:

Ansys generates mechanical failure counterplots for selected design life, with a maximum safety factor of 15 shown. However, suppose the stress in a particular location exceeds the material strength. In that case, the safety factor ratio decreases to less than 1, indicating a risk of failure in that part of the model before the end of the design life. Fig.13 shows the numerical value of the safety factors for each composite socket sample. The best results came from combining (2 Perlon layers + 2 bamboo layers+2 Kevlar layers +2 bamboo layers + 2 Perlon layers), likely because Kevlar fiber has many great properties.

In contrast, lamination (2 Perlon layers + 2 bamboo layers +2 Glass layers +2 bamboo layers + 2 Perlon layers) had the lowest safety factor of 3.06 compared to the other groups. Fig.14 illustrates the variation of the safe and unsafe regions in the prosthetic socket composites under walking pressure.

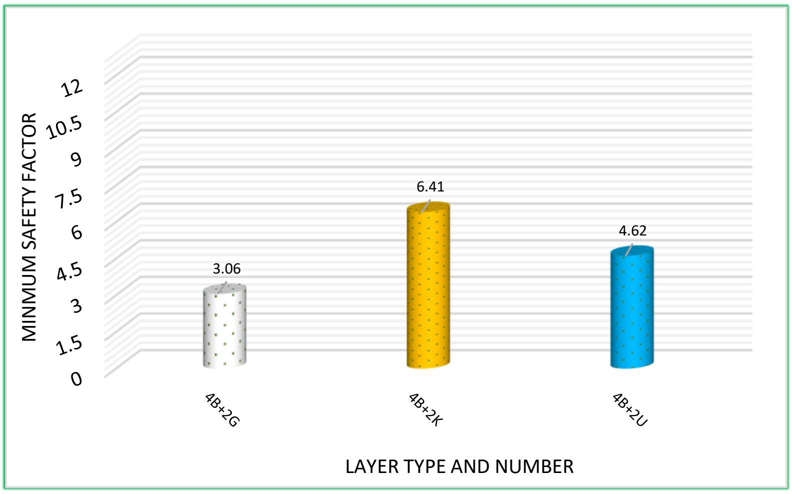


Fig.13: *Safety factor for modified laminated composite.*

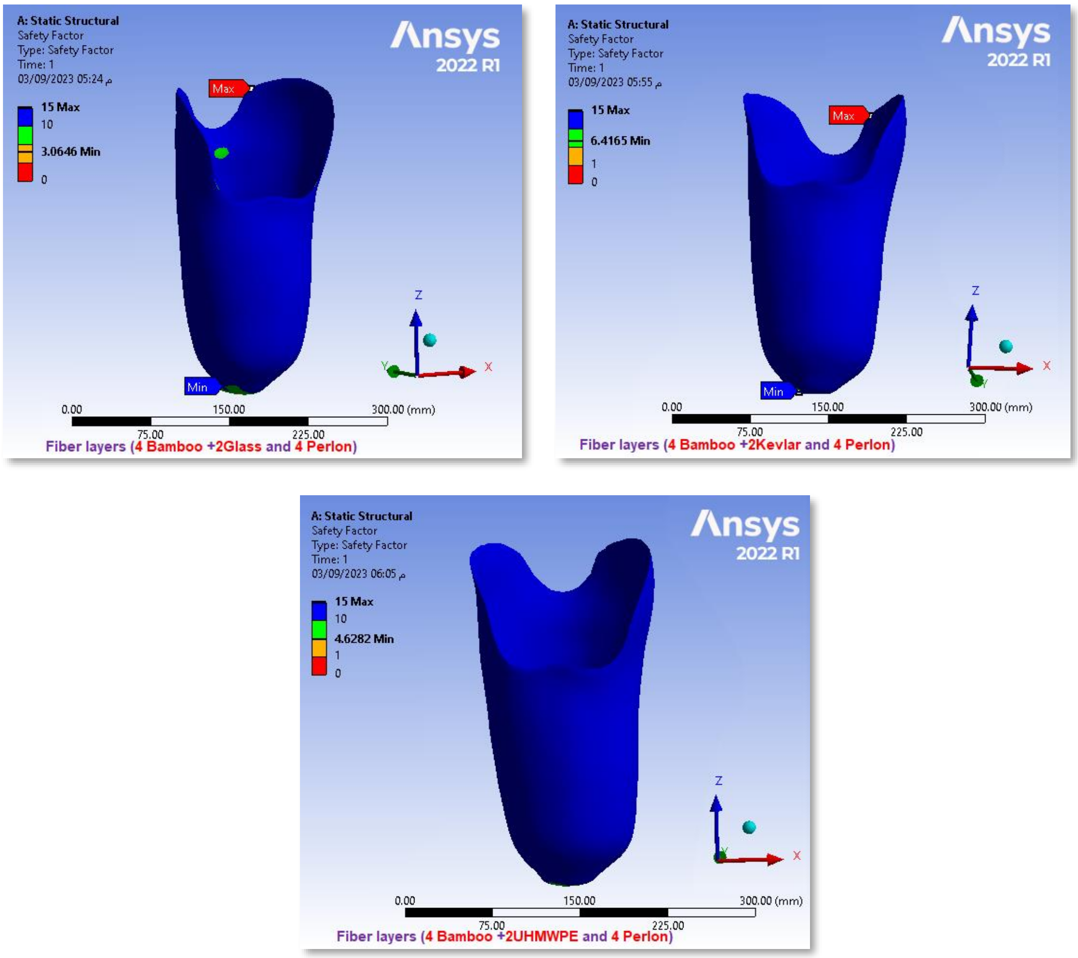


Fig.14: *Prosthetic Socket Safety Factor.*

6. Conclusions.

According to the study's findings, the prototype of the laminated-material prosthetic socket serves as a safe and comfortable alternative for patients. Moreover, it is an environmentally friendly option that employs natural materials that are eco-friendly and recyclable. The study's principal conclusions comprise the following:

- Group (A) characteristics show a significant improvement, with a 65% increase in ultimate stress (σult), a 62% increase in modulus of elasticity (E) and a yield strength (σy) improvement of almost 64%. While the number of layers of bamboo fiber remains the same, these improvements are noticeable compared to Group C.
- The ultimate tensile strength and elastic modulus of the below-knee socket changed greatly when the materials that made it up were changed. The stacking arrangement of four layers of Perlon, four layers of bamboo, and two layers of Kevlar fibers gave the highest tensile strength, 179 MPa, and elastic modulus (3.473 GPa).
- The largest elongation percent value was 9.21%, from a mix of four ramies and two glass fibre layers.
- The composites reinforced with bamboo and Kevlar fibers showed the best results in experiments and computer simulations. This makes them strong candidates for improving the mechanical properties of prosthetic sockets below the knee.

- As seen in all the tested laminated composite samples with different lamination distributions, the lowest safety factor value for the below-knee socket is around 3.06. This level is safe and acceptable.

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