Application of Natural Fibers as Composite Reinforcement Materials in Fabrication of Trans-Tibial Prosthetic Sockets

Bhagirath S. Jana, Makarand Saraf

Department of Prosthetics and Orthotics, All India Institute of Physical Medicine and Rehabilitation, Mumbai, India
E-Mail: bhagirathjana2999[at]gmail.com

Abstract: ***Prosthesis is an artificial device that replaces a missing body part, which may be lost because of trauma, disease, or a condition present at birth (congenital disorder). The main component of the prosthesis is the prosthetic socket which is the device that joins the residual limb (stump) to the prosthesis and is manufactured using thermoplastics or thermosetting plastics. The constant need for change or adjustment may become costly if the material used is expensive. Conventional composite materials used for prosthetic limb sockets include acrylic resins, glass and carbon fibers, which produce harmful gases and dust in their manufacture and are very costly[3]. Bio-composites (natural fiber composites) from local and renewable resources offer significant sustainability; industrial ecology, eco-efficiency, and green chemistry are guiding the development of the next generation of materials, products, and processes. The growing global environmental and social concerns, high percentage of exhaustion of petroleum resources, and new environmental regulations have forced the search for new composites, compatible with the environment. In this study we have used natural fibers derived from bamboo plants to manufacture prosthetic sockets and compared their performance with prosthetic sockets manufactured using fiber glass [2, 7]. The results obtained from the comparative tests were highly encouraging.***

Keywords: Prosthetic socket, fiber-reinforced polymer composite, bamboo fiber extraction and treatment, epoxy as a matrix, compression load testing

1. Introduction

In medicine, a prosthesis is an artificial device that replaces a missing body part, which may be lost because of trauma, disease, or a condition present at birth (congenital disorder).[6] Usually loss of limbs takes place in the upper or lower extremities. In the lower extremities, below-knee (trans-tibial amputations) are more common than above the knee (trans-femoral). Prostheses are intended to restore the normal functions of the missing body part. The components of a prosthetic device are prosthetic socket, adaptors, joints, pylon and foot. The prosthetic socket is the device that accommodates the residual limb (stump) and is the most important part of the prosthesis. The socket is made according to the condition and shape of the residual limb. Prostheses are made lightweight for better convenience for the amputee. Some of the materials used for fabrication of prosthetic sockets include:

1. Plastics
-Polyethylene
-Polypropylene (Co-Polymer Polypropylene)
-Acrylics
2. Wood (early prosthetics)
3. Leather (early prosthetics)
4. Lightweight materials
-Titanium
-Aluminium
5. Composites
-Glass Fiber Reinforced Composites with Polyester resin as matrix material
-Carbon Fiber Reinforced Composites with epoxy resin as a matrix material

Prosthetic sockets are made using thermoplastic polymers or thermosetting polymers combined with different types of fibers acting as the reinforcing materials, making the material a composite material. The thermoplastic materials have a high molecular weight and low density. They can be plasticized by using pressure and/or temperature; polyethylene (PE) and polypropylene (PP) are among the most commonly used thermoplastics[7].

Thermosetting plastics are primarily employed as the matrix material of composite materials in the fabrication of prosthetic sockets. Composite materials are made up of two or more materials with quite diverse properties that are combined. The multiple materials work together to give the composite material its unique features, yet you can recognize the different materials apart within the composite since they don't dissolve or blend into each other.

Composite materials usually consist of two phases, the first is the primary phase which forms the matrix and inside this, the secondary phase is embedded. The primary phase in polymer matrix composites used for manufacturing prosthetic sockets is usually formed by thermosetting plastics like polyester resin, epoxy resin or acrylic resin[3, 12]. The secondary phase is the embedded phase which is also known as the reinforcing agent because it provides strength to the composite materials. The materials most commonly used for the secondary phase in prosthetic sockets are glass fiber, carbon fiber, Kevlar, etc. Composites are used in industries because they are weight saving (high specific properties), corrosion resistance, and fatigue properties. Composites can be very strong and stiff, yet very light in weight, so ratios of strength to weight and stiffness to weight are several times greater than steel or aluminium.[3]

When making prosthetic sockets out of composite materials, a technique known as lamination is used, and the end product is referred to as a composite material laminate. The matrix component, which is usually in the form of thermosetting plastic, the reinforcement component, which is usually in the form of layers of reinforcing materials such as carbon fiber, glass fiber, and other materials, and the binding agent are the main components of a polymer matrix composite material.[7]

This research is based on the manufacturing of prosthetic sockets using natural fibers as the reinforcement material in composite materials. We have attempted to compare the trans-tibial prosthetic socket manufactured using bamboo fiber-reinforced composites with the prosthetic sockets manufactured using glass fiber reinforced composites.

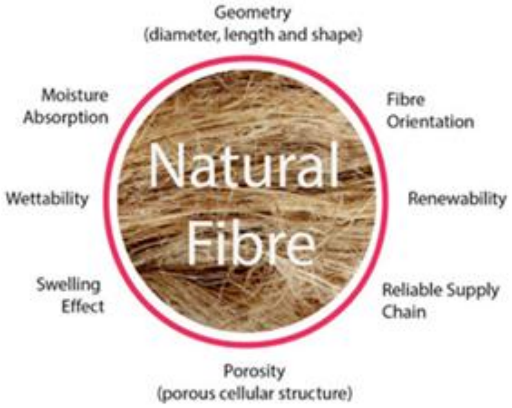
2. Literature Survey

Natural fibers are of interest to scientists nowadays due to their advantageous traits such as low cost, high strength to weight ratio, low density per unit volume, non-corrosive property, and acceptable specific strength, in addition to their renewable and degradable characteristics. The main concern nowadays is about the environment which is stimulating scientific research towards the design and proposal of new engineering materials for construction, packaging, furniture, and automotive industries. The research on using natural fibers such as banana, bamboo, jute, kenaf, etc. in various manufacturing industries has developed an interest in biomedical engineering.[2, 3, 7] Research is done using coir-polyester composites to fabricate helmets, roofing and post-boxes. Kenaf fiber-reinforced composite is also been researched as bio-composite material used in various applications such as building and construction. Trenchless restoration of underground pipelines, cabinets, machine coverings, seat backings, bumpers, baggage shelves, and many other applications have been made using jute fiber-reinforced composite materials. Research work was carried out to develop, manufacture, and assemble a prototype car whose body panels were made of natural fibers composites.

3. Problem Definition

Composite materials come in a variety of types, with natural and synthetic fibers being the most commonly used fibers. Synthetic fibers are man-made fibers that are generated by chemical synthesis and are then classified as organic or inorganic based on their content. Glass fibers (GFs) are the most commonly used synthetic fibers because they have excellent strength, durability, thermal stability, impact resistance, and wear qualities. Carbon fiber-reinforced polymer (CFRP) composites are used in a variety of industries, including aerospace, automobiles, sports, and many more.

These fibers emit carbon, are costly and are damaging to the environment. The processing of these fibers is time-consuming and difficult. It also has the drawback of being discarded in the end.[3] These synthetic materials emit a lot of carbon dioxide, which raises the carbon dioxide concentration of the atmosphere, which is already high owing to other pollution sources. When synthetic items are dumped in the water, they represent a hazard to marine life. As a result, employing natural fibers in place of synthetic fibers in the future development and improvement of composite materials is one of the ways to prevent worrisome dangers, as they are non-polluting. Natural fiber consumption would aid in the removal of contaminants from the environment. As a result, scientists are currently concentrating their efforts on finding natural fibers that may be utilized instead of synthetic fibers in a variety of applications, including the production of prosthetic sockets[4, 8, 12] Natural fibers have a variety of characteristics that distinguish them from synthetic fibers, including reduced weight, cost, toxicity, pollution, and recyclability.[2, 4] Natural fibers are gaining popularity due to their inexpensive cost, as well as a growing awareness of environmental issues such as "renewable and recycling resources," as well as "carbon dioxide emission reduction," and so on. The cultivation, extraction, and processing procedures have a significant impact on the qualities of natural fibers. The mechanical and chemical properties of these composites have been a focus of recent research.[7, 12]



4. Methodology / Approach

Composites incorporate fibers as reinforcement materials which are embedded in the matrix structure and can be classified according to fiber length. Composites with long fiber reinforcements are termed continuous fiber-reinforced composites, while composites with short fiber reinforcements are termed discontinuous fiber-reinforced composites. Fibers can be placed unidirectional or bidirectional in the matrix structure of continuous fiber composites, and they take loads from the matrix to the fiber in a very easy and effective way. There are numerous natural fibers available, so the goal was to select a fiber that should be easily obtained and have high specific strength.[3]

4.1 Choice of fiber

A wide range of natural fibers are available like: bamboo, banana, jute, ramie, cotton, soya, etc. There are numerous challenges on how to extract these fibers, their availability, and their processing. Bamboo fibers were chosen because of their strength and availability. Bamboo is one of the woody plants which offer several advantages such as ease of growth in diverse climates, durability and low-cost material when compared to others. Bamboos are abundantly growing plants mainly in South America and Asia. Bamboo fibers have also caught the attention of researchers due to their advantages over synthetic fibers. It is entirely renewable, environmentally friendly, non-toxic, cheap, non-abrasive, and fully biodegradable. The table below presents the properties of bamboo that are comparable to other natural fibers such as Kenaf, jute, and sisal.[1]

Fibres	Density (g/cm^3)	Tensile Strength (MPa)	Young's Modulus, E (GPa)	Specific Young's Modulus, E (E/d)	Elongation at failure (%)	Moisture absorption (%)
E-glass	2.55	2400	73	29	3	-
Bamboo	0.6-1.1	140-230	11-17	10-28	-	8.9
Hemp	1.48	550-900	70	47	1.6	8
Jute	1.46	400-800	10-30	7-21	1.8	12
Kenaf	1.45	930	53	36.5	1.6	-
Ramie	1.5	500	44	29	2	12-17
Sisal	1.33	600-700	38	29	2-3	11

From the table it can be seen that the Specific Young's modulus (Specific E) of bamboo is comparable to that of the E-glass fiber. This means the bamboo fibers have a high stiffness with minimum weight. The availability of bamboo is abundant but the knowledge of extracting the fibers is limited because very few efforts have been devoted to the extraction of these fibers from bamboo plants. Because of this, only a handful of studies are available on the properties of these fibers and their use as reinforcement for polymers.[1, 9]

4.2 The extraction of bamboo fiber

The form of extracted bamboo fiber will determine the final forms of composite whether as laminated fiber-reinforced composites, short or randomly oriented fiber or formed into a sandwich structure. The common forms of extracted bamboos are strip, flake, long fiber, short fiber, and powder.[1, 5]

In contrast, there is limited knowledge regarding bamboo fiber extraction, only a few investigations have been done with different processes to define the mechanical properties and the usage of bamboo fibers as a reinforcement material in polymer matrix composites.

Fibers were extracted by roller mill hand technique to get long fibers. Bamboo was first wetted in slightly alkaline water for 24 hours and then it was extracted by hand process. Since it was extracted mechanically due to limited resources available for extraction, the length, width, and the thickness were slightly uneven.[6] Fibers were then woven into a mat with longitudinal fiber orientation, with a

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fiber orientation of 90° to the transverse plane. Bamboo matting is not made tightly with the aim that the resin lubricates all parts of the mat during the resin lamination process. The maximum tensile strength is achieved when the bamboo fiber orientation is at 0°, a condition where the fiber is parallel with the load applied.[1, 5, 9]

4.3 Matrix choice for the composite

Epoxy Resin was chosen as a matrix for bamboo fiber composite since it has good results for binding with fibers. Epoxy resin, the most popular choice of resin, is biodegradable. After a test was conducted, it was discovered that two bacteria are the cause for the biodegradation of epoxy resin. Rhodococcus rhodochrous and Ochrobactrum anthropic are the two bacteria responsible for the breakdown of epoxy resin. Epoxy resin Epofine and Epoxy hardener Finehard (10: 1) was sourced from the local market for the lamination procedure.[10]

Specimen	Ultimate Force (kN)	Tensile strength (MPa)
Bamboo Fiber Epoxy Composite	2.7	25.171
Glass Fiber Epoxy Composite	3.12	18.87

4.4 Treatment of fibers

Treatment of fibers was very important after the extraction because the lack of interfacial adhesion between bamboo fibers and epoxy resin degrades the strength of bamboo/epoxy composite. Fiber pre-treatment is a promising way to reduce moisture absorption of natural composites.[1, 6]

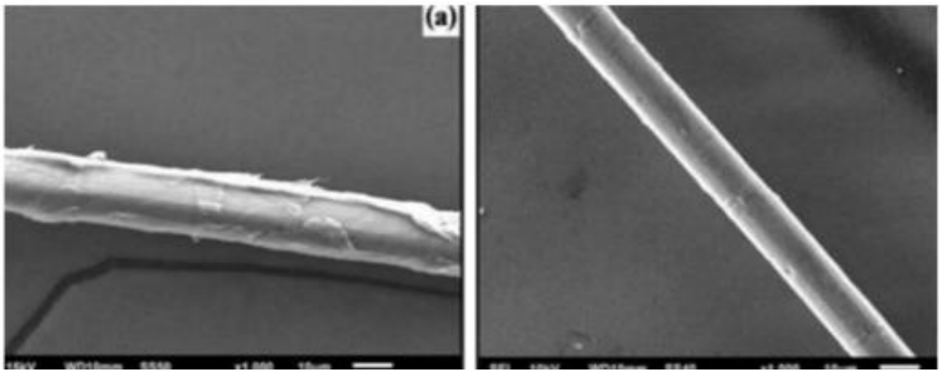


Image of a) untreated and b) treated fibers

Thus, chemical treatment was introduced to enhance the bonding between these two interfaces. According to the research and literature, chemically treated bamboo fiber with 5 wt. % sodium hydroxides (NaOH) for 1 hour has been proven to be optimum for the fabrication of bamboo fiber composites. It was found that the treatment increases the effective surface area for better bonding with matrix material by removal of bonding materials such as hemicellulose and lignin. Alcohol treatment for fibers is also a safe and easy method. The effectiveness of fiber greatly increases with alcohol treatment, the bamboo fiber is then soaked in 90% alcohol solution for 15 minutes then sun-dried until it is completely dry, to remove the waxy layer and increase the strength and elasticity of the fiber.[9, 10, 11]

4.5 Socket Fabrication Procedure Using Bamboo Fiber Epoxy Composite

Prosthetic sockets for the lower extremity are usually manufactured using composite material laminates using the lamination technique described above or Thermoforming of Thermoplastic materials on a positive modified model of the patients stump. In general, the procedure for manufacturing prosthetic sockets is as follows:

i) Measurement of patient anthropometric data
ii) Obtaining a negative impression of the patient's stump (Cast)
iii) Modifying the cast based on biomechanical principles- Positive mould making
iv) Fabrication of Socket over the modified mould

The following were the procedure followed in the fabrication of the prosthetic socket using bamboo fibers combined with epoxy resin to form a composite material socket. In the making of the socket, the layup of materials through layers are as follows:

1. Right 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. 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 giving thickness and a smooth inner layer of the socket.

3. Over the stockinette layers, a mat of bamboo fibers was applied covering the entire mould followed by repeating layers of stockinette.

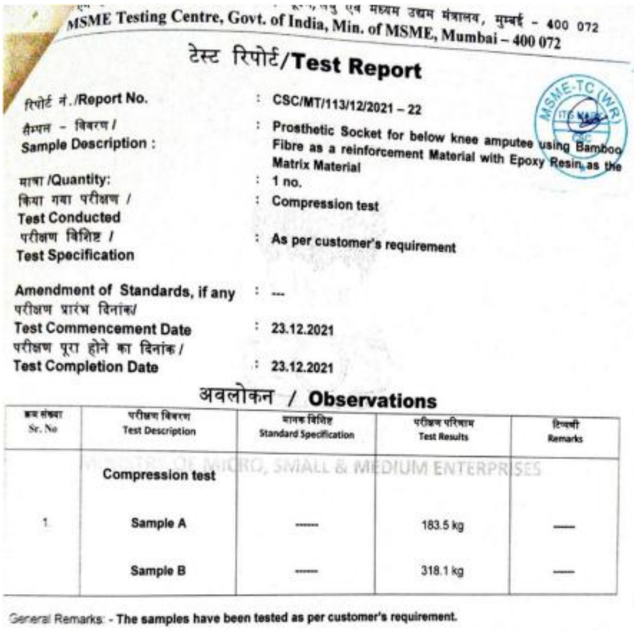
4. 4. After the outermost stockinette layer, a layer of PVA bag is applied which forms a medium through which the epoxy resin can be incorporated into the laminate. This plastic coating aims in containing the fluid interface and as a smooth outermost protective layer against dirt.
5. The matrix material is prepared by mixing epoxy of 500g with the pigment as required following hardener of 50g resulting in a 10: 1 ratio of epoxy to hardener mixed well before pouring.
6. The process begins with the pouring of the matrix mixture into the arrangement of socket material through the pouring channel of the outer PVA. The matrix mixture begins to dampen the layered composition of the socket material and is evenly distributed with manual manipulation. The vacuum engine is turned on and adjusted to a pressure of-80 bar until all the matrix mixture had seeped into the socket material evenly and there is no visible air trapped.
7. After the lamination process is finished, the fabricated socket is allowed to dry at room temperature. The curing time of the epoxy resin used is 24 hours. When the socket has dried, the socket is removed from the positive mold. After the socket is removed from the positive mold, the finishing process is carried out so that it is ready for testing or fitting to the prospective user.

5. Result

A socket receives compressive, tensile, torsional, shear, impact and a combination of all however, the main load received by the socket is the compressive load from the user's weight that is transferred via stump to the socket. As a result, it is required to test the socket's failure owing to the load it gets.

Maximum compressive strength testing is used to determine the maximum load that the prosthesis socket may withstand before it becomes fatally damaged. The test done was a compressive load failure test at the MSME Testing center, Mumbai. The following results are given below:

Sample A: Glass fiber polyester composite socket handles the compression of 18.35 kN.



सू.,लघु एवं मध्यम उद्यम मंत्रालय, मुम्बई - 400 072
MSME Testing Centre, Govt. of India, Min. of MSME, Mumbai – 400 072

टेस्ट रिपोर्ट/**Test Report**

रिपोर्ट नं./Report No. : CSC/MT/113/12/2021 – 22
सैम्पल - विवरण / Sample Description : Prosthetic Socket for below knee amputee using Bamboo Fibre as a reinforcement Material with Epoxy Resin as the Matrix Material
मात्रा /Quantity: : 1 no.
किया गया परीक्षण / Test Conducted : Compression test
परीक्षण विशिष्ट / Test Specification : As per customer's requirement
Amendment of Standards, if any : ---
परीक्षण प्रारंभ दिनांक/ Test Commencement Date : 23.12.2021
परीक्षण पूरा होने का दिनांक / Test Completion Date : 23.12.2021

अवलोकन / **Observations**

क्रम संख्या Sr. No	परीक्षण विवरण Test Description	मानक विशिष्ट Standard Specification	परीक्षण परिणाम Test Results	टिप्पणी Remarks
	Compression test			
1	Sample A	------	183.5 kg	——
	Sample B	------	318.1 kg	——

General Remarks: - The samples have been tested as per customer's requirement.

Sample B: Bamboo fiber epoxy composite socket handles the compression of 31.81 kN.

6. Conclusion

The socket manufactured using bamboo fiber epoxy composite can withstand more load than the socket made of glass fiber polyester composite, according to the results bamboo fibers can provide an opportunity for economic development in rural regions due to their use in a broad spectrum of engineering applications. Although relatively high strength and lightweight were once the most essential parameter to accomplish, other factors like environmental sustainability, integrated energy, and fatigue resistance are now becoming more important. Furthermore, bamboo reinforced polymer composites, particularly bamboo / epoxy composites, have mechanical qualities comparable to synthetic fiber polymer composites. As a result, the developed manufacturing technique can be used to create lower limb prosthesis socket items.

7. Future Scope

Bamboo fibers have not been researched as reinforcements in polymeric composites despite their high potential, because of their unavailability of knowledge. Various aspects affecting the ultimate physical characteristics of bamboo reinforced polymer, such as fiber length, fiber orientation, and fiber treatment, has been investigated. Fibers should be extracted in such a way that their length, width, and thickness are uniform so that they can be woven into both horizontal and vertical placements. Chemical treatment is used to optimize the adherence of the matrix to the bamboo fibers. To improve the laminate's interfacial qualities, research should be conducted that focuses on optimum chemical concentration, particularly alcohol treatment which is safe and economic to conduct. Further research should be done with other natural fibers as a composite polymer matrix and compare the strength with synthetic fibers so that it can replace them in the upcoming era of materials.

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Authors Profile

Mr. Bhagirath S. Jana, Educational Qualification: Bachelors in Prosthetics and Orthotics (BPO), Clinical Experience: 4 Years, Work as an Associate Prosthetist and Orthotist at Otto bock Healthcare India.

Mr. Makarand Saraf, Educational Qualification: Masters in Prosthetics and Orthotics (MPO) Teaching, Experience: 15 Years, Clinical Experience: 21 Years, Approved as Lecturer/ Guide for Bachelors of Prosthetics and Orthotics course and Masters of Prosthetics and Orthotics course by Maharashtra University of Health Sciences, India.