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# Properties of natural fibre composites for structural engineering applications

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ABSTRACT

Since the last two decades, many researchers have refocused on using natural fibres, as reinforcements for cementitious and polymer based structural materials. The use of natural fibres for structural applications is not modern. Long before a century ago people in many small towns in China and Korea already mixed straws with mud to build walls in villages. However, at that time there was no systematic way to study the fundamental mechanism and interpret how natural fibres strengthen structures and what processes should be adopted to maximize the performance of natural materials. Currently, nevertheless natural fibre reinforced polymer (NFRP) composites have been widely used in automotive and building industries, it is still a room to promote them to high-level structural applications like primary structural components of aerospace and maritime structures. It is difficult to evaluate the quality of natural fibres, which generally extracted from the nature, and thus it is challenging to develop a generic formula to predict the structural and mechanical properties of NFRP composites. Hydrophilic and hydrophobic properties of natural fibres and polymers, respectively, cause poor bonding interaction at interface. Traditional shear-lag model was popularly used to study the stress transfer mechanism between fibre and matrix of advanced composites. However, such model is not applicable to NFRP composites due to the imperfect shape of nature fibres along their longitudinal direction and irregular shape of fibres' cross section. In this paper, analysis on different aspects in related to the use of natural fibres for real life engineering applications is given. Basic analytical models focusing on the stress transferability in composites are also discussed to provide an insight for researchers and engineers to understand the design and requirements of using natural fibres for structural applications in the future.

## 1. Introduction

Advanced composites, owing to their high specific strength –to-weight and specific-stiffness-to-weight ratios, are very popular for different types of engineering applications. High strength fibres commonly used in aircraft and aerospace engineering industries, are carbon, glass and Kevlar. These fibres provide strong tensile strength to support tensile and bending stiffness of composite structures. Polymer-based matrix act as a cushioning material to protect these high strength and brittle fibres against an impact. Besides, matrix is used to absorb vibration energy to keep rigid structures safe under seismic attacks. Despite the fact that advanced composites bring advantages to many engineering applications, there are three major issues commonly criticized by the public:

i) Advanced composites are hardly to be recycled, which may cause serious environmental problems after disposal;
ii) the structures made of advanced composites may be over-strength in particular using carbon fibre reinforced polymer (CFRP) composites and
iii) there is relatively high materials cost of advanced composites for domestic products.

Therefore, fibres extracted from the nature have emerged in the past decades aiming at replacing traditional high strength synthetic fibres to form a new class of natural fibre reinforced polymer (NFRP) composite. The growing awareness of environmental concerns is also another element to force the engineering sectors to develop new materials from natural resources that are either reusable or renewable. Regarding this, natural fibres and biodegradable polymers have become an attractive topic recently.

In the last few decades, many research groups in the world have developed promising materials, which are made of biodegradable fibres and polymers to form new types of bio-composites (some articles have

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stated as "green composites"), to replace conventional materials. In many countries, newly established policies have also encouraged business units to pay much attention to save energy and materials to sustain the life of our planets [1]. Incentive in tax reduction is also another way to motivate different commercial units to design and make products with "Green" components. The cost of natural fibres is relatively low as they are abundant and from renewable resources compared with other synthetic fibres. Therefore, such remarkable advantages of NFRP composites enhance their commercial and research potentials. Accordingly, natural fibres and biodegradable polymers have become emerging materials in the composite community.

## 2. Types of natural fibre

Natural fibres can be classified into two types: animal-based fibres and plant-based fibres. Cocoon silk, chicken feather, wool and spider silks are commonly used as animal-based fibres, which mainly target to biomedical applications such as implants. These bio-products are required to be either bio-resorbable (some articles name it as "bio-degradable"), which means the ability to break down and assimilate back into the body or biocompatible, to avoid being harmful to human body. Lau et al. [2] have developed a new bone fixator by using cocoon silk fibre-reinforced Polylactic acid (PLA) to form a fully bio-resorbable polymer composite. The purpose of this fixator is to hold two pieces of broken bone in place. Once the bone cells on the fracture surfaces start growing, the fixator will be resorbed by the human body with time. The rate of bio-resorbability is dependent on the amount of silk fibre used. This bio-resorbable property could minimize the necessity of secondary surgery to remove steel fixators in the traditional bone fixation process.

Plant-based fibres, including jute, hemp, sisal kenaf, coir, flax, bamboo and banana, are commonly mixed with polymers to form NFRP composites for making domestic products, of which cost and strength are the most concerning factors. Such fibres are classified as renewable sources and can be extracted from the nature without damaging environment, they could be a substitution of glass fibre diverse engineering applications as the mechanical properties of the NFRP composites are comparable to glass fibre reinforced polymer (GFRP) composites (Table 1).

## 3. Structure of natural fibres

Natural fibres have complicated structures in microscopic view. As showed in Fig. 1, by grinding a kenaf bark fibre, a core of lumen is wrapped by different layers of cell wall with different microfibril orientations, which give the strength to the fibre subject to different loads [3]. Similar to other layer systems, the microfibrillar angle governs the tensile strength of nature fibres. Ramesh [4] has provided a detail table to compare the properties of different plant-based natural fibres with different microfibrillar orientations. The elongation at break increases with microfibrillar angle. The relationship between the microfibrillar angle and the tensile modulus of different natural fibres is shown in Fig. 2. It is noticeable that tensile modulus of NFRP composites would be higher when all microfibrils are aligned along the fibre's direction, where tensile loading is applied.

Moreover, microfibrils are not identical as they are comprised of crystalline and amorphous regions, in which the former one determines the strength of fibre while latter one is relatively soft and formed by irregular molecular chains (Fig. 1). The internal structure of natural fibres is contingent upon the age and origin of the plants and climate conditions. Ho et al. [3] have shown a clear chart on the family of natural fibres commonly used in different engineering applications.

Recently, Bamboo fibre has attracted much attention compared with other types of natural fibres (Fig. 3). Low density, low cost, high mechanical strength and high growth rate are its advantages. The most excellent merit of this type of plant is that its ability of producing oxygen and absorbing carbon dioxide are approximately three times as compared with other plants, which help stabilize the green house problem in certain extent. Obviously, many tiny holes are seen on bamboo (Fig. 3b). However, high porous nature, high moisture content, difficulty of extracting fine and continuous fibre, and thermal degradation during the manufacturing process are its disadvantages to broad applications [5].

Literally, such problems may exist in other types of natural fibres, which results in reducing the strength of resultant composites. Despite the green message is straightforward, product manufacturers hesitate to use these kinds of composites due to several aspects, such as geometrical and mechanical properties, consistent and stable supply chain of natural fibres, bonding properties between the natural fibres and matrix, and the durability of NFRP composites served in different harsh environments [2]. These aspects become the reference for the users to evaluate their usability and manufacturability.

**Table 1**
Basic properties of natural fibre and glass fibre [1].

| | Density ($g/cm^3$) | Tensile strength (MPa) | Elastic Modulus (GPa) | Elongation at Break (%) |
|---|---|---|---|---|
| Jute | 13–1.5 | 200–770 | 20–55 | 2.0–3.0 |
| Sisal | 1.5 | 100–800 | 9–22 | 3.0–7.0 |
| Kenaf | 1.4–1.5 | 930 | 53 | 1.6 |
| Coir | 1.2 | 180 | 4–6 | 30.0 |
| Flax | 1.5 | 350–1040 | 28–70 | 2.0–4.0 |
| Hemp | 1.5 | 690 | 30–70 | 1.5–4.0 |
| Bamboo | 0.6–1.1 | 140–230 | 11–17 | 4.0–7.0 |
| Carbon | 1.4 | 4000 | 230–240 | 1.4–1.8 |
| Aramid | 1.4 | 3000–3150 | 63–67 | 3.3–3.7 |
| E-glass | 2.5 | 1200–1500 | 70 | 2.5 |
| Epoxy (Thermoset) | 1.10–1.40 | 41–90 | 3.0–6.0 | 1–6 |
| Polyester (PE) (Thermoset) | 1.04–1.46 | 35–100 | 2.1–4.4 | 1–3 |
| Hemp/Epoxy Vf = 40% | – | 75 | 3.33 | – |
| Jute/Epoxy Vf = 40% | – | 58 | 4.0 | – |

## 4. Interfacial bonding properties of NFRP composites

The mechanical properties of NFRP composites are directly governed by their interfacial bonding properties between the natural fibre and its surrounding matrix. Many different types of micro mechanical tests such as single fibre fragmentation test, single fibre pull out test, the micro-bond test and the single fibre compression tests are commonly used to examine the interfacial bonding properties of fibre reinforced composites.

Beckermann and Pickering [6] have studied the bonding property of hemp fibres treated with a surface coupling agent, maleic anhydride modified polypropylene (MAPP), which enhances the bonding between the fibres and matrix. The fragmentation test was conducted to find out the critical length ($L_c$) of the fibre, in which the stress can be fully transferred from the matrix to the fibre if an embedded length (L) is equal or great than $L_C$ once a composite is loaded. The fragments appear in different lengths from Fig. 4. Different surface morphology of hemp fibres could be found with various surface treatments (Fig. 5) [7].

Liotier et al. [8] have studied the fibre/matrix interface in NFRP composites. Wettability of resin on the surface of fibre was studied by taking the surface energy of a solid ($\gamma_s$) and the surface tension of a liquid ($\gamma_L$) into account. The results showed that treated natural fibres would have a better bonding performance as compared with untreated fibres due to large contact angle ($\theta_A$).

### 4.1. Fibre pull-out model

Traditionally, the performance of fibre/matrix interface can be