Mechanical Behaviour of Coir and Glass Fibre Reinforced Polymer Composites Material: A Literature Study

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Abstract: Glass fibre reinforced polymer (GFRP) has been commonly adopted in marine engineering for vessel hull as a high performance and durable material. Otherwise, the several efforts to replace the synthetic fibres with the natural fibres due to the increase of environmental awareness and oil resources depletion have been conducted. The natural fibres such as coir, jute, hemp, ramie and bamboo which are available in abundance, biodegradable and low density is the main reason to explore the application potential in shipbuilding sectors. In this paper, the mechanical behaviour of coir and glass fibre reinforced polymer composites material is reviewed. The surface modification of the natural fibre are also reviewed and it is found that the surface treatment is an alternative method to improve the natural fibre mechanical properties for successfully utilizing the natural fibre in marine and shipbuilding applications. From this review of both coir and glass as a reinforced fibre, it is concluded that a focus on the material properties of coir fibre combined with the glass fibre as a hybrid material is needed if the behaviour of vessel hull composite structures during sailing operation and other sources of external load is to be fully understood.

1 INTRODUCTION

Knowledge and methods for making composite compositions as raw materials of ship hull construction have been developed since 1970. At that time the lamina layer was made using fiberglass which was chopped and given wet resin using a manual coating technique known as a hand layered method. The design and application of composite materials on ships is able to provide better performance in terms of speed, transport/cargo capacity, and fuel consumption which is more economical when compared to ships made of steel or aluminium. These improvements can be achieved because the composite material offers a lighter construction weight. Otherwise the FRP hull surface texture is smooth. Therefore it might reduce the magnitude of the ship resistance.

Composite construction that is widely used in ship construction is glass fibre reinforced polymer / plastic (GFRP). In reinforced polymer/plastic fibres, fiberglass is a component which is used to support loads, otherwise the function of polymers/plastics is stabilizing, bonding and distributing loads on the glass fibres, and provide water-resistant conditions in GFRP construction. Stiffness and rigidity of glass material fibres depends on the fibre material and the position of the fibre in the lamina layer. The ideal GFRP composite model is generally used as a sandwich construction consisting of a lightweight core which is enclosed in two rigid and strong layers (top and bottom layer) in the form of GFRP laminate. The adopted core material for hull construction can be PVC (polyvinyl chloride), polyurethane foam and balsa wood. This sandwich material offers a light weight construction but it has very good strength and rigidity.

Since 1990, the natural fibres have been introduced as an alternative reinforcing material in the composite laminate. The natural fibres can be used as a replacement of glass fibre or applied as an alternative fibre for core-layer material on the composite laminate board. Natural fibres such as hemp fibre-epoxy, flax fibre-polypropylene (PP) and china reed fibre-PP have been applied to the automotive industry, because it offers lower price and lighter density. Natural fibres also offer environmentally friendly properties through reducing

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the dependency on non-renewable energy sources, low pollutant emissions, low green-house gas emissions, and the ability to be degraded naturally (biodegradability). Natural fibres have attracted scientists to be investigated for its capability to be implemented as alternative materials in the manufacturing and construction industries. The use of natural fibres, especially coconut fibre (coir fibre), as reinforced fibres of the core material of fibre reinforced plastic (FRP) composite material is an alternative method to achieved environmentally friendly vessel hull construction.

Based on its mechanical properties the strongest and most rigid FRP material is carbon fibre reinforced polymer. Several lamina configurations on FRP material can be carried out to obtain the desired mechanical properties. Figure 1 shows that FRP material does not show a clear yielding point compared to steel material. This characteristic of FRP materials can provide advantages and disadvantages in ship construction. Some other advantages of FRP material are corrosion resistance. The woven roving fibre composites have better rigidity and impact resistance. The addition of natural fibres to FRP material can influence the mechanical properties of FRP. Therefore, the use of natural fibres as additional reinforcing fibres in FRP material needs to be done in-depth studies so that they can be used in ship construction in receiving dynamic loads such as wave bending moments, green water loads, vibrations, collisions and explosions.

Although FRP composite strength is able to withstand dynamic loads, the mechanical characteristics of FRP are sensitive to strain rate and temperature. The tensile strength, modulus of the young and the shape of the stress-strain diagram of the FRP will change when subjected to loads that have different strain rates. Furthermore the addition of natural fibres in FRP material can also have an effect on its mechanical characteristics. Based on this, it is necessary to study to find out more about the effect of strain rate and temperature on FRP material accompanied by the addition of natural fibres as reinforcement (hybrid coir fibre and glass fibre) to the mechanical properties of the material.

2 MECHANICAL PROPERTIES OF GFRP

The GFRP composite material consists of glass fibers that function as reinforcement which is integrated with polymer resin (called matrix). Fillers also exist apart from fibres and matrices used to increase interactions, reduce manufacturing costs and improve the mechanical properties of composites (Bakis, 2002; Binshan, 1995; Richardson, 1996). However, the nature of filler metal material has an insignificant relationship to the composite material properties, (Paciornik, 2003).

E-glass fibre is the most widely used type of fibre almost 95% of total glass fibre production, (Varma, 1984). The traveling glass is basic shapes with continuous filament bundles. Chopped strand mat (CSM) is a sheet that contains randomly chopped fibres, tied together adhesive. Figure 1 gives an example from failed GFRP coupons that show the roving and CSM micro.

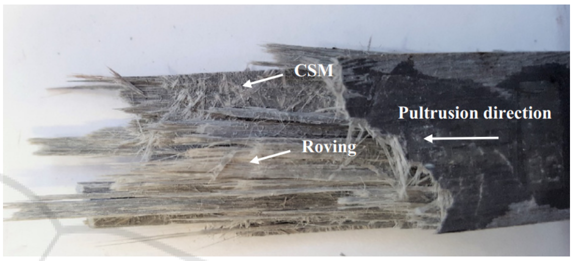

Figure 1: The failed GFRP composite material.

Polymer resins are non-fibrous parts of FRP that bind fibres together and are also known as matrices or binders. Polyester, vinyl ester and epoxy are the most widely used thermoset polymers, (Bank, 2006; Edwards, 1998), and the choice of polymer type depends on the mechanical properties required and the manufacturing methods available. Vinyl ester has been shown to have a higher rigidity than polyester or epoxy, regardless of the shape of the fibre, (Bank, 1989; El-Habak, 1991), but is more expensive. Therefore, polyester resin or polyester and vinyl ester mixtures are generally used in the production of GFRP composite profiles. However, in situations where there may be endurance issues, vinyl ester and epoxy can be the preferred choice

Considering the orthotropic nature of the GFRP composite material, and its production, there are many factors that can influence its material properties. Several investigations since the 1990s have shown that the main factors are:

- fibre and resin type;
- fibre volume fraction (FVF);
- fibre orientation;
- sample geometry (including shape, length to width ratio);
- strain rate;
- interface properties; and
- temperature

These works include Naresh et al. (2018; 2017), Chelladhural et al (2018), Danie Roy et al (2018), Windyandari et al (2019), Zakki et al (2019a; 2019b), Bazli et al (2017), Hasan et al (2019), Rossini et al (2019), Zhang et al (2019), Reis et al (2018), and Kim et al (2015). In the works done, there were focused on the strength of the GFRP material which is applied to the civil structure and marine structure. However the published work on the material properties of GFRP combined with natural fibre is limited and often conflicting.

In the literature that concern on the influence of strain rate to the GFRP laminate composite, it is found that the strength is rise as the strain rate is increased regardless the resin type, and fibre type (woven roving/CSM), (El-Habak, 1991). Nevill et al (1971), and Binshan et al (1995), present that the material strength increase significantly increase at high strain rate (above 10^{-1}). Furthermore, Sierakowski (1997), has reviewed the strain rate (below 20 s^{-1}) effect of composite laminate that show a little increase in GFRP strength. The elastic modulus of GFRP laminates is also founded have similar tendency as the strength GFRP. It can be found that the elastic modulus of GFRP laminates is increasing when strain rate is increased, (Dorey, 1986; Hsiao, 1998). Regarding the reviewed literature, it can be seen that there has been several research to understand the influence of strain rate on the GFRP composite materials.

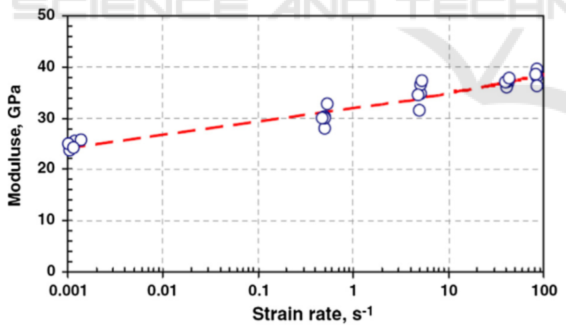

Figure 2: The longitudinal modulus of GFRP composites under compression, (Shokrieh, 2009).

In the case of longitudinal elastic modulus, the strain rate from 10^{-4} to 10^{2} s^{-1} has increased the elastic modulus in the range of 20%-55%, (Rotem, 1971; Shokrieh, 2009; Tay, 1995). The similar increase also can be found on the smaller strain rate, (Armenakas, 1973; Amijima, 1980; Kawata, 1981; Bai, 1984; Li, 1995; Takeda, 1995; Yuanming, 1996; Huang, 2004). However, the other studies have shown a slightly different tendency on the influence strain rate on the elastic modulus. Hayes and Adams (1982), present that the strain rates 60s^{-1} to 80s^{-1} have decreased the initial longitudinal modulus of 20%. Kumar et al (1986), shows that the dynamic modulus are 29% and 16% lower than the corresponding quasi static value on the strain rates 0.0002 s^{-1} and 265 s^{-1}, respectively. Ou et al (2015), present that the longitudinal modulus is decreased from strain 0 to 40 s^{-1}. However the elastic modulus is increased after 40 s^{-1}. The average value of all dynamic moduli can be shown in Fig. 2 and Fig. 3

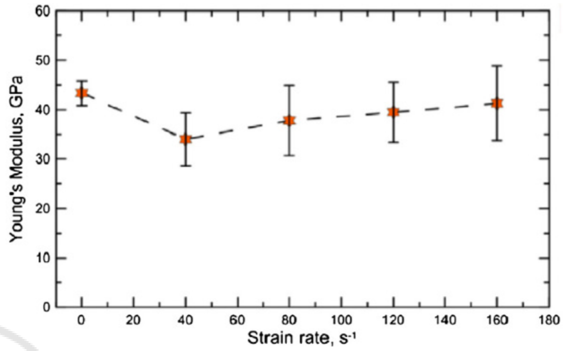

Figure 3: The longitudinal modulus of GFRP composites under tension, (Ou, 2015).

According to the literature review, the strain rate have influence the elastic modulus of GFRP material. It can be seen that the longitudinal elastic modulus have been reviewed more than the transverse modulus. Moreover, most researches generally deal with quasi static and high strain rate instead of the intermediate strain rate. Generally, it can be concluded that the increase of strain rate might cause an increase in the elastic modulus of GFRP laminate composite, especially for high strain rate. However the exception still can be found on such literature.

In the case of fibre orientation, the off axis fibre orientation have shown less sensitivity to the change of the strain rate compared to zero degree orientation. However, it cannot be found the research that was focused on the modulus of off axis of combined coir and glass FRP on the intermediate and high strain rate.

In the case of resin type and internal reinforcement structure, the several studies show that there is a significant influence on the elastic modulus of the GFRP laminate composite. The most common resin that was used as matrix is epoxy resin. The epoxy resin has higher stiffness characteristics that the other type of resin. The different sequence of fibre stacking also shows the different strain rate sensitivity to the elastic modulus.

Finally the reviewed researches usually provide an assumption that the GFRP composite have the same properties under compressive and tensile load.

The assumption should be validated on the experimental studies.

3 MECHANICAL PROPERTIES OF COIR FIBRE

Coir is natural hair-fibre that is obtained from the outer skin (endocarp), or husks of coconuts. Coir is also known as "Kokos" or "Coco". Coconuts are the fruit of *Cocos nucifera* tree, the tropical plant *Arecaceae* (Palmae) family. *Cocos nucifera* have grown many especially in the coastal area in the tropical countries. The first coir factory for manufacturing coir products was found to be established at Alleppy, in Kerala in 1858, (Rajan, 2007). The word coir comes from "Kair" - Malayalam, a south Indian language (Tamil, *kayiru*) which means the umbilical cord. Coir fibres or coconuts are categorized in the group of hard structural fibres, and lignocellulose.

Coir fibre is physically and visually looked as coarse, stiff and reddish brown coloured fibres. It contains of smaller threads with diameter of 12 to 24 microns and the fibre length of 0.01 to 0.04 in. Coir fibre is composed of lignin, substance of plant, and cellulose. The advantage of coir fibre is the capability to stretch beyond its elastic limit with no rupture damage. It seems like having the power to overcome the permanent deformation. Coir fibres also have good resistance to microbial degradation and salt water. Therefore the coir fibre is suitable to be adopted as material of marine industry product.

Morphologically coir fibres are contains of micro fibrils that is organized the aggregates of cellulose molecules. The micro fibrils are embedded in a non-cellulosic polysaccharides and lignin matrix. The lignin is located between the non-saccharide parts of the cell wall as the unique polymer. The large lignification can be found on the middle lamella and primary cell, and the least is found on the secondary wall. The lignification function is to strengthen the cell wall through cementing the cellulose micro fibrils and protecting them from the chemical and physical deteriorations.

As a natural cellulosic fibre, the coir fibres firstly have an almost white colour. The increasingly lignified process will made the coir fibre colour become darker. The coir have red-brown colour in the dry husk of matured coconuts. Bismarck et al (2001), study the thermal stability of coir fibre that presented the two-step decomposition curve and the degradation onset between 190 ºC and 230ºC.

The preliminary study on the chemical changes of the lignocellulose of coir fibre was made by Menon and Pandalai (1936). The lignocellulosic coir fibre is biodegradable. Since the coir fibres have high lignin contents, coir has better durability compared to the other natural fibres. The advantages of the coir fibres are include:

- 100% natural fibre,
- Biodegradable material
- Obtained from renewable resources
- High water retention
- Biological deterioration resistant
- Good heat and noise insulator

The chemical composition of coir such as cellulose, cellulosan, lignin and hemicellulose is depended upon the coconut age, (Menon, 1936). It is different with the jute fibres that have uniform chemical composition at all stages of the growth process. The physical properties and the chemical composition of coir fibre can be seen in Table 1 and Table 2, respectively.

Table 1: Physical properties of coir fibre, (Bledzki, 1996; Chand, 1994).

Length [cm]	15 – 20
Diameter [µm]	100 – 450
Density [g/cm^3]	1.15
Tenacity [g/tex]	10.0
Tensile strength [MPa]	131 – 175
Young modulus [GPa]	4 – 6
Elongation at break [%]	15 – 40
Swelling in water [%]	6 – 8.5

Table 2: Chemical composition of coir (wt%), (Ugbolue, 1990; Varma, 1984; Varma, 1986).

Lignin	41 – 45
Cellulose	36 – 43
Pectin	3 – 4
Hemicellulose	0.15 – 0.25
Microfibrillar/spiral angle [deg]	41 -45
Moisture content	8.0

4 SURFACE MODIFICATION OF NATURAL FIBRES

As an alternative material for the replacement of synthetic fibres, natural fibres have any kind of advantages such as low density, low cost and biodegradable. However natural fibres also have some drawbacks which are include poor compatibility with different matrices, high moisture absorption and swelling capability that may cause crack in brittle matrices. Since the drawbacks of natural fibres can decrease the laminate composite quality, therefore some techniques have been adopted to modify the surface of natural fibres, especially to reduce moisture absorption capability and to improve adhesion characteristics with polymer matrices. There are three kind of surface treatment for surface treatment of the natural fibres which are included: physical techniques, chemical techniques and biological treatments.

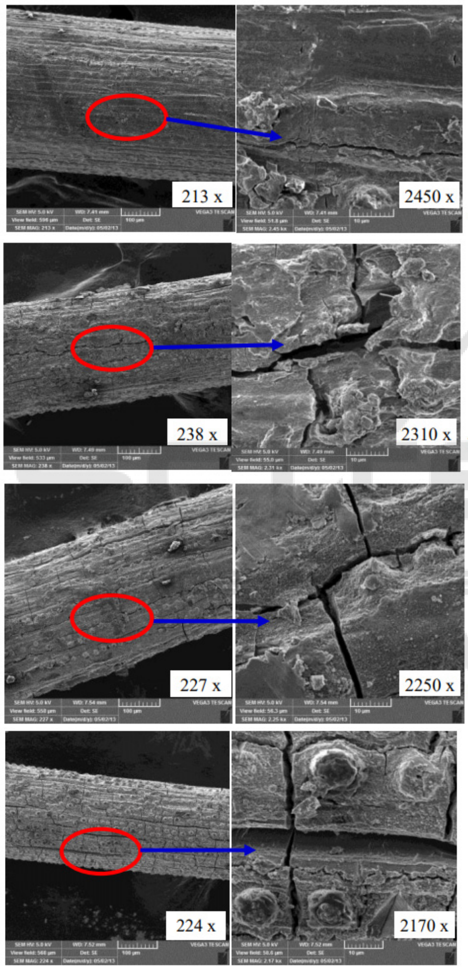

Figure 4: Surface morphology of coconut fibre with alkali treatment, (Muhammad, 2015).

A physical technique that is used for surface treatment of natural fibres is known as plasma treatment. The plasma treatment which has been used to modify the surface of various natural fibres can improve the mechanical properties significantly, (Oliveira, 2012; Shahidi, 2013). In addition, plasma treatment introduced functional group that form strong covalent bond with the matrix, therefore the plasma treatment may produce the strong fibre/matrix bonding interface to improve the quality of laminate composite. Surface etching on the plasma treatment can improve the roughness of the fibres surface. Therefore the better mechanical interlocking between the fibres and matrices is obtained.

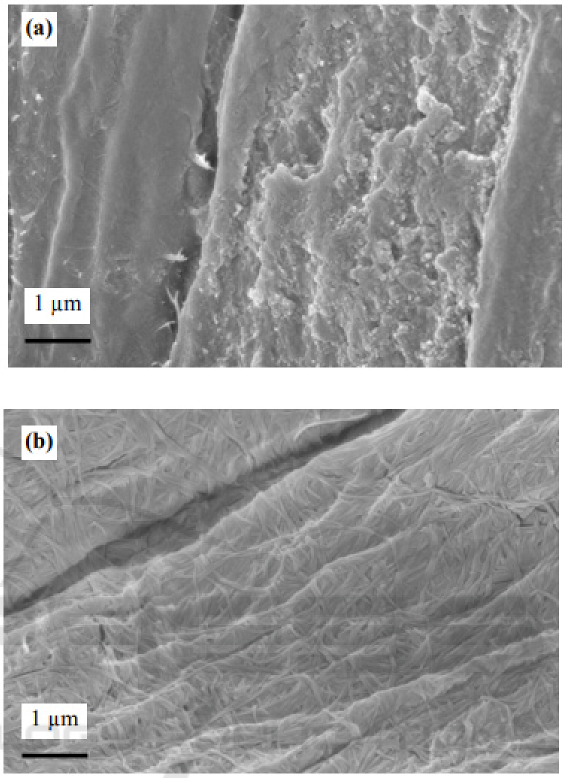

Figure 5: SEM micrographs of hemp fibre surfaces; (a) Natural hemp fibre; (b) Hemp fibre after bacterial cellulose modification, (Pommet, 2008).

Chemical treatments have been adopted for the surface treatment of natural fibres. The used of various chemical constituents such as alkali, silane, water repelling agents, peroxides, permanganates have been proved able to improve the mechanical properties significantly. The alkali treatments modified the crystalline structure of natural fibres through removing the weak components such as hemicelluloses and lignin of the fibre structure, (Xue, 2007). The water repelling agents can reduce the moisture absorption and natural fibres swelling. Furthermore the silane coupling agents can improve the fibres-matrices interfacial interaction through strong chemical bonding formation, (Xie, 2010). The illustration of the surface morphology of coir fibre with alkali treatment can be seen in Fig. 4, (Muhammad, 2015).

Finally, biological treatment is adopted to modify the natural fibre surface characteristics. The biological treatment is conducted through depositing cellulose nano fibrils on the surface of the sisal and hemp fibres, (Pommet, 2008). The cellulose nano fibrils were used as substrates for the fermentation process of bacterial cellulose. The significant improvement was made on the interfacial adhesion with polymeric matrices such as cellulose acetate butyrate and polylactic acid. The percentage of deposition of bacterial cellulose is about 5-6% on the natural fibre surface. The illustration of bacterial cellulose modification on the natural hemp fibres can be seen in Fig. 5.

5 CONCLUSIONS

In this paper, the existing literature on the material properties of GFRP and coir fibre has been reviewed. The coir fibre shows great opportunity to be applied in marine structures such as boat hull structures, due to the excellent durability and high water retention. As an alternative material, it is important that its behaviour under stress applied at different strain rates, different direction and combined with the GFRP as hybrid material is more fully understood. Although many researches have been found on the mechanical properties of GFRP laminates, there is yet limited studied on the dynamic properties of coir fibre and hybrid coir-glass fibre.

In comparison with other natural fibres, coir fibres as a high lignified material have better resistant to chemical and microbial attack. The advantage of coir fibre compare to synthetic fibres such as glass fibres, talc and mica are acceptable strength properties, low cost, low density, good thermal properties, non-abrasivity, enhanced energy recovery and biodegradable. Surface treatment of natural fibres that made bio-softened coir can be blended with the synthetic fibres as a hybrid material for producing the marine structures.

According to the advantage and the mechanical properties of coir fibre, it is indicated that coir fibres is able to be adopted as an alternative reinforced fibres in composites material. The surface treatment of natural fibres such as physical, chemical and biological treatment methods, and also the mechanical characteristics of the coir fibres and the hybrid material (coir-glass reinforced polymers) is the subject of interest for the future research in order to fully utilize the advantages of natural fibres in composite materials and to successfully utilize it in the marine industrial application.

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