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Effect of water absorption on Mode I interlaminar fracture toughness of flax/basalt reinforced vinyl ester hybrid composites

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ABSTRACT

In this study, the influence of water absorption on the Mode I interlaminar fracture toughness of flax and basalt fibre reinforced vinyl ester hybrid composites is presented. Three types of composite laminates namely, flax fibre reinforced vinyl ester (FVE), flax fibre hybridised basalt unstitched (FBVEu) and flax hybridised basalt stitched (FBVEs), fabricated by vacuum infusion technique are investigated. Double cantilever beam (DCB) tests were performed to evaluate the Mode I critical energy release rate (G_{IC}) and the crack length (R-curve) by using three different data reduction methods. It was found from the experimental results that the Mode I fracture toughness initiation and propagation of water immersed FVE composites were decreased by an average of 27% and 10% respectively, compared to the dry specimens, whereas the fracture toughness propagation of water immersed FBVEu and FBVEs composites were improved by approximately 15% and 17% compared to dry specimens. The fractured surface and delamination of different composites were evaluated by using scanning electron microscopy (SEM) and X-ray computed micro-tomography (μCT). The results showed that basalt fibre hybridisation has positive effects on durability and the moisture resistance of natural fibre composites.

1. Introduction

Recent developments in natural fibre reinforced composites (NFRCs) have led to renewed interest in semi-structural and structural applications especially in the automotive and construction sectors as an alternative material to synthetic fibre composites. The reasons for this shift to the use of natural fibre composites are due to increased global awareness and new environmental legislation requiring manufacturers to adapt sustainable materials [1]. Furthermore, due to increased consumer awareness and the need for lightweight components in order to reduce overall CO_2 emissions, the automotive industry is leading the way in using natural fibre composites and bio-composites. The hybrid composites developed by using flax and basalt fibres not only provide weight savings but also offer more environmentally friendly composites which can further be applied in the marine and construction industries [2].

In a recent extensive review relating to the use of natural plant fibres for structural applications, it has been highlighted that there have been several research works conducted focusing on the development of NFRCs for structural applications [3]. The review concluded that natural (bast) fibres have superior mechanical properties due to their chemical and structural composition which contains high cellulose and aspect ratio with low micro-fibril angles. Thus, natural fibres can be most appropriate to be used as reinforcements in the composite industries as these natural fibres provide the best potential integration of light weight and low cost, with high specific strength and modulus [4]. However, NFRCs have low-durability and inherently absorb high moisture which can reduce their properties and thus affect the long-term performance. For example, increased moisture content in natural fibres causes swelling and alters their dimensions because of the poor adhesion/compatibility between the hydrophobic matrix and hydrophilic natural fibres [5,6]. Previous studies have reported the effect of water absorption on the properties of NFRCs, such as hemp [7], jute [8] and flax [9]. These reports have shown that increased moisture uptake of natural bast fibres is due to high cellulose and voids content, and the mechanical properties such as tensile and flexural strength would be significantly lowered as a consequence of weak interfacial adhesion between fibre and matrix.

Delamination is one of the most prevalent failure mechanisms in composite laminates. It usually occurs due to dynamic loadings, such as low-velocity impact when the structure is subjected to cyclic or static loading conditions [10]. Sufficient ability to absorb fracture energy is an important requirement for structure design,

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which is dependent on the fibre and matrix properties. Because of this, the use of natural fibres in the form of non-woven mats and short fibres is limited in non-structural applications [11]. However, in order to obtain high performance composites in terms of stiffness and strength, it is important to use long continuous unidirectional fibres or woven non-crimp fabrics [12].

Many research works have been carried out on the hybrid system in composites materials [13–18] which contain two or more different types of natural and synthetic fibres in a similar matrix. Due to their unique attributes of achieving tailored material performance, hybrid composite systems have recently received significant attention. Common reinforcements used in hybrid systems include carbon and glass fibres as well as other nanoparticles. In recent years, basalt fibre has been one of the popular reinforcements used to hybridise natural fibre composites. The main reason for this include, but are not limited to basalt fibre being originated from nature and has less environmental damage compared to non-renewable reinforcements such as carbon and glass fibres. In addition, this fibre has high chemical stability as well as resistance to high temperature, and it is produced from commonly occurring rock [19]. Fiore et al. [14] showed that the addition of two external layers of basalt fibre enhanced the mechanical properties of flexural and tensile compared to glass fibre reinforced composites without hybridisation.

From the studies reported in the literature, very limited work has been documented in the analysis of fracture toughness behaviour of natural fibre composites. In addition, there are no reported works on the effect of water absorption on the fracture toughness of NFRCs. Also, very few studies have been undertaken to improve the fracture toughness of NFRCs by chemical treatment [20,21] and fibre or matrix hybridisation [22–24]. Li et al. [20] have conducted the fracture toughness test to investigate the effects of fibre surface treatment of sisal fibre reinforced vinyl ester composites. They found that the permanganate and silane treated systems improved the fracture toughness in comparison to the untreated systems with critical strain energy release rate (G_{IC}) of 1682.2 J/m^2–1488.3 J/m^2 and 1158.7 J/m^2, respectively. However, Silva et al. [21] reported that the alkaline treatment contributed to lower the fracture toughness of the sisal fibre reinforced polyurethane composites. This behaviour was attributed as a result of improved interfacial adhesion between fibre and the matrix which affected debonding and fibre pull-out which reduced the fracture energy absorption. Hence, the use of thermoplastic matrix material such as polypropylene and polyurethane leads to a decrease of mechanical properties caused by a weak bond to natural fibres, and they also have lower mechanical properties compared to thermosets [12]. Wong et al. [23], for example, noted that the interlaminar fracture toughness (G_{IC}) of flax fibre reinforced hyperbranched polymers (HBP) with poly($_L$-lactic acid) (PLLA) was significantly increased when modified and blended together. Moreover, the toughness properties were improved due to better wetting of the fibres by these matrices. From a review of this literature, it can be concluded that of central importance in using natural fibre composites in structural applications is the measurement of their fracture toughness behaviour.

Amongst the several textile methods of inserting through-thickness fibre reinforcements, stitching, knitting and weaving are the methods used to improve the interlaminar fracture toughness. It is likely that the most common of these techniques is stitching because of its versatility and convenience [25–29]. By using stitching through-thickness reinforcement, the fracture toughness of the composites has been improved as a result of providing a more integrated composite structure [30]. However, it has been observed in the previous studies that stitching can cause in-plain fibre damage and create resin-rich regions which can lead to to a reduction of the flexural, compressive and tensile properties [30,31]. Indeed, it is difficult to predict the influence of stitching on the in-plane mechanical properties owing to many factors, such as the type of the composite laminates, fabrication techniques and also the important parameters of stitching (stitch density, pattern, span, yarn diameter, type of thread) [32]. More recent published work by Ravandi et al. [33] examined the effects of stitching through-thickness reinforcement using natural fibres on Mode I interlaminar fracture toughness of flax fibre/epoxy composites. It was found that the interlaminar fracture toughness of woven flax composites was significantly higher than glass fibre composites. Moreover, flax yarn stitches exhibited improved fracture toughness of the laminates compared to cotton thread stitches.

The work reported in this paper is aimed at characterising the Mode I interlaminar fracture toughness of flax fibre and flax/basalt reinforced vinyl ester composites. To the best of our knowledge, there are no reported works on the influence of water absorption relating to fracture toughness behaviour of flax fibre and basalt fibre hybridised composites. Herein, for the first time this report presents a detail investigation into the effects of water absorption behaviour and its impacts on the interlaminar fracture toughness of hybrid and stitched composites laminates. The findings from this study will help designers and manufacturers towards using natural fibre composites in structural and semi-structural components in terms of understanding their mechanical properties, as new composite based products emerge. Double cantilever beam (DCB) tests were carried out under Mode I loading to determine the crack growth resistance curves (R-curves) and the critical energy release rate values for both initiation ($G_{IC\ init.}$) and propagation toughness ($G_{IC\ prop.}$). The fracture mechanisms of the surface and the delamination of composites were characterised by using scanning electron microscopy (SEM) and X-ray computed microtomography (μCT).

2. Experimental procedure

2.1. Materials

The matrix material used in this study was based on commercially available vinyl ester, trade name: Scott-Bader Crystic VE676-03, obtained from Scott-Bader. Accelerator was added at 2% by weight along with Triganox 239 at 2% by weight as the catalyst. Woven flax and woven basalt fibres were used as the reinforcements (±045°) biaxial stitched non-crimp fabrics of 600 g/m^2 in weight, supplied by Net Composites Ltd. A PTFE layer of 20 μm thick was used to simulate a crack in the middle of reinforced panels. Table 1 presents the chemical and structural composition of different natural fibres commonly used as reinforcements in composites.

2.2. Fabrication of composite laminates

The flax and flax/basalt hybrid laminates were fabricated by the vacuum infusion technique. This technique is beneficial to produce composites with high volume fraction of fibres and it enables a better strength-to-weight ratio with less void content [4]. The resin-infused laminates were prepared using a balanced layup with the reinforcement of flax and basalt fibres, as illustrated in Fig. 1. The process started with the dry pack of layers which were placed on top of a glass plate which had previously been treated with a release agent (Multishield). This pack was then covered with a layer of nylon peel ply release and a diffusion mesh was added to the top of the peel ply to help shorten the infusion time. The tape rectangle was then covered with a vacuum bag, the inlet pipe capped off and a vacuum of −29″ Hg applied. Once the resin had been mixed with accelerator and catalyst, the inlet pipe was sub-