Composites Science and Technology 154 (2018) 117–127

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: http://www.elsevier.com/locate/compscitech

Investigation into Mode II interlaminar fracture toughness characteristics of flax/basalt reinforced vinyl ester hybrid composites

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ARTICLE INFO

Article history:
Received 29 September 2017
Received in revised form
15 November 2017
Accepted 16 November 2017
Available online 21 November 2017

Keywords:
Flax fibres
Hybrid composites
Fracture toughness
Delamination

ABSTRACT

In this work, the influence of water absorption of flax and flax/basalt hybrid laminates is presented with the aim to investigating the Mode II interlaminar fracture toughness. Four types of composite laminates namely, neat vinyl ester (neat VE), flax fibre reinforced vinyl ester (FVE), flax fibre hybridised basalt unstitched (FBVEu) and flax hybridised basalt stitched (FBVEs), were fabricated by vacuum assisted resin infusion technique. Three-point-end-notched flexure (3ENF) tests were performed to evaluate the critical Mode II strain energy release rate (G_{IIC}) and the crack length (R-curve) at dry and wet conditions, by using two data reduction methods. The morphology of delamination and the fracture shear failure of composite laminates were evaluated using scanning electron microscopy (SEM) and X-ray micro computed tomography (μCT). The results obtained that the fracture energy of FBVEu composites, $G_{IIC\ init.}$ and $G_{IIC\ prop.}$ were increased by 58% and 21%, respectively compared to that of FVE dry specimens. Moisture absorption phenomenon caused increasing in the ductility of matrix that improved the resistance to crack initiation. However, this was inverted to a reduction in the fibre/matrix interfacial strength of FBVEu wet composites and a deterioration in the delamination resistance to crack propagation. The critical strain energy release rate of neat VE increased from 157.84 J/m^2 to 239.85 J/m^2 with reinforcement of flax fibre composites. The experimental results confirmed that basalt fibre hybridisation enhanced the durability and water repellence behaviour of natural fibre reinforced composites.

1. Introduction

In the last two decades, natural plant fibres as reinforcements in polymer composites have been extensively used towards achieving sustainable green materials. The key factor that drives in focusing on the use of natural plant fibre-reinforced polymer (FRP) composites over synthetic FRPs is ecological advantages: availability, renewable resources and biodegradability, which reduce large amounts of embodied energy [1]. Among the different types of natural fibres, bast fibres (flax, hemp, jute and ramie) derived from plants are most commonly used in different applications such as automotive, marine and construction, because of their attractive properties in terms of weight (low density) and performance (high specific strength and modulus) [2]. In recent years, there has been resurgence for using these fibres as reinforcement in composite materials. This renewed interest is attributed to increasing prices of non-renewable oil products and new strict environmental regulations [3].

Despite aforementioned advantages, some of the main challenges for the use of natural plant fibres are susceptibility to moisture absorption that leads to poor adhesion between fibre and matrix interface due to the presence of hydroxyl and polar groups in composites. The diffusion of water in the composite materials can cause swelling and plasticisation that could effect the mechanical and thermal properties [4]. Dhakal et al. [5] studied the effect of water absorption on the mechanical properties of flax and jute reinforced bioresin composites. The results showed that the percentage of moisture uptake for jute composites were higher than that of flax samples. The flexural strength and modulus for both samples were decreased after immersed in distilled water at 25 °C for 961 h. The flax wet samples reduced 40% of its strength and 69% of modulus, whilst the jute wet composites lost 60% of its strength and 80% of modulus. In addition, Chow et al. [6] found that the tensile strength and modulus of sisal reinforced polypropylene composites decreased after water immersion at elevated

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https://doi.org/10.1016/j.compscitech.2017.11.016
0266-3538/

temperature of 90 °C for different durations. The decreased properties can be attributed to the plasticisation of sisal fibre composites interface and swelling of fibres.

Natural FRP composites are still limited in non-structural applications due to their higher moisture absorption, lower strength and stiffness properties [7]. To tackle these issues, a hybridisation of natural cellulosic fibres with mineral fibres which have superior ageing resistance and thermal resistance were investigated to improve the mechanical properties. At the present time, there is a significant interest for using basalt fibres as hybridising material into natural FRP composites due to their excellent properties such as mechanical, chemical, thermal and acoustic insulation [8–10]. Fiore et al. [8] investigated the effects of basalt fibre hybridisation as a double external layers on the impact and flexural properties of flax reinforced composites under different environmental conditions. They found that the impact, flexural strength and modulus of flax/basalt hybridised composites were higher than flax without hybridisation by 28%, 71% and 49%, respectively. Similar work carried out recently by Fiore et al. [9] on jute-basalt fibre reinforced hybrid structures highlighted that all composite laminates performed lower in their mechanical properties with increasing ageing time but the sandwich structure of basalt hybrid performed best in terms of their mechanical performance compared to other generic composites. The properties enhancement realised can be related to positive attributes of basalt fibre. Basalt fibres are obtained from mineral through melting rocks, thus non-hazardous/toxic which can be considered as environmentally friendly material compared to glass fibres [11,12]. Therefore, basalt hybridisation into natural fibres can serve as an effective means to enhance the mechanical properties and moisture resistance of composites by promoting improved fibre/matrix interface. From these benefits, the capability of the basalt fibres to be used as a hybridisation for a structural reinforcement material is extremely expected [13].

Based on reviewed literature, it is evident that most of the studies have been carried out investigating the properties of natural FRPs exposed to the durability of moisture absorption [5,6,12,14,15]. Majority of these studies focus on the mechanical properties, very few works on fracture toughness have been carried out on natural FRP composites [16–20]. Moreover, there are hardly any research works that comprehensively studied the effect of water absorption on the interlaminar fracture behaviour of natural FRPs in terms of understanding their properties of fracture energy and crack length [21]. The delamination and crack propagation of natural FRP composites depends on several factors such as fibre volume fraction [17,19], fibre/matrix interface [16,22], fibre orientation angle [17,23] and mechanical properties of the materials [19,24]. Study by Liu and Hughes [17] revealed that the fracture toughness is strongly dependent on the stacking sequence and weave configuration of the textiles when composites tested under different weft or warp directions. Hughes et al. [25] investigated the fracture toughness of bast fibres of hemp and jute reinforced polyester composites as well as unsaturated polyester neat in comparison to chopped strand mat (CSM) glass fibre laminates. The results showed that the critical strain energy release rate G_C, was significantly higher for CSM laminates than hemp, jute and unreinforced polymer composites of 10.21, 1.84, 0.97 and 0.10 kJ m^{-2}, respectively at 20% fibre volume fraction. Almansour et al. [26] highlighted that non-woven flax/basalt hybridised laminates improved the fracture toughness compared to non-woven flax composites without hybridisation using 3ENF testing. It was reported that the critical strain energy release rate G_{IIC}, and stress intensity factor K_{IIC} were increased for flax/basalt laminates by 12% and 33%, respectively compared to flax composites without hybridisation. Wong et al. [19] characterised short bamboo fibre reinforced polyester composites and neat polyester using compact tension (CT) specimens with different fibre volume fractions from 0 to 60 vol% at 4, 7 and 10 mm fibre lengths, respectively. The results showed that the highest fracture toughness of hybrid composites was achieved with improvement of 340% compared to neat polyester, whereas the fracture toughness decreased incrementally of 10, 7 and 4 mm at 50, 40 and 10 vol% with critical stress intensity factors, K_{IC}, of 1.73, 1.62 and 1.50 MPa $m^{1/2}$, respectively.

In general, delamination corresponds to stable and unstable crack between the plies in composite applications ascribed to inherent defects from the materials or through process fabrication and also damage incurred during the service life when composite undergoes to different loading and environmental conditions [27]. Therefore, there are some methods to reduce the interplay delamination by using toughened matrix, woven fabrics, through-thickness stitching and interleaving [28]. Previous studies have investigated the effect of stitching on the Mode II interlaminar fracture toughness of FRPs [29–31], but natural fibres composites still not yet reported. It was reported that the addition of stitching improved the mode II delamination resistance up to four times and observed stable crack propagation of FRPs, which depended on the parameters of stitch density, thread type and dimeter [31]. Ravandi et al. [32] have reported the effect of through-thickness natural fibre stitches on the low-velocity impact of woven flax reinforced epoxy composite laminates. Stitching of flax yarn led to decrease the intralaminar fracture toughness of woven flax composites about 16%, whereas the cotton yarn stitching was reduced by only 5%.

This paper aims at investigating the Mode II interlaminar fracture toughness of woven flax and flax/basalt reinforced vinyl ester composites. In addition, the influence of water absorption on the fracture toughness behaviour of composite laminates was evaluated. Three-point-end-notched flexure (3ENF) tests were carried out to measure the crack length and the critical strain energy release rate, G_{IIC} (initiation and propagation). The shear fracture surfaces of woven flax and flax/basalt hybrid and stitch composites were analysed to understand the failure mechanisms of delamination and crack growth resistance.

2. Materials and experimental procedure

2.1. Materials

Woven flax and basalt fibres were used as the reinforcements of fibre orientation $[\pm 45]_{3s}$ biaxial stitched non-crimp fabrics of 600 g/m^2 in aerial weight, supplied by Net Composites Ltd and Basaltex NV (Belgium), respectively. The matrix used was vinyl ester and obtained from Scott-Bader, named Crystic VE676-03. Crystic accelerator ‘G’ was added with the resin to accelerate gel time at 2% by weight and mixed along with Triganox 239 at 2% by weight as the catalyst. The Teflon layer of PTFE in 20 μm was used to simulate a crack in the reinforced composite panels.

2.2. Fabrication of composite laminates and test specimens

Composite laminates of flax fibre reinforced vinyl ester (FVE), flax fibre hybridised basalt reinforced vinyl ester, unstitched (FBVEu) and flax fibre hybridised basalt reinforced vinyl ester, stitched (FBVEs) were fabricated using vacuum assisted resin transfer moulding (VARTM) technique. In FVE composite laminates, six layers of woven flax were used with fibre weight content of 100%. The hybridised composites of FBVE were used by replacing two external layers of woven flax by two layers of woven basalt, with fibre weight ratio of flax/basalt, (70:30). Stitched panels were included three single rows at 2 mm intervals after the crack tip of 5 mm by using sewing machine. Stitching was done prior to