ABSTRACT

The mode I interlaminar fracture toughness of stitched and unstitched composite laminates of continuous UD flax fiber and epoxy matrix was experimentally and numerically investigated. A twistless flax fiber yarn was used for stitching purpose. The mode I interlaminar energy release rate of the unstitched and stitched laminates was experimentally determined through Double Cantilever Beam (DCB) test. Tensile test was conducted to characterize the tensile properties of the dry and resin impregnated forms of the stitch yarn. A 3D Finite Element (FE) model of DCB specimen to analyze delamination propagation of stitched flax fiber laminate was developed using cohesive element with nonlinear softening law and embedded 2-node beam element. The out-of-plane flax yarn stitching was found to generate a twofold increase in the delamination resistance of the composite laminate at a medium stitch density. The FE analysis results agreed well with the experimental results, where a good fit between the predicted and experimental R-curves were achieved.

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INTRODUCTION

In the past decade, the use of Natural Fibres (NFs) from plants as reinforcement in polymer composites have become more popular thanks to their promising properties such as high specific stiffness, good acoustic and vibration damping, and eco-friendly characteristics. Despite the attractive properties of natural fibers, the use of these fibers have been more or less limited to the short fiber composites in non-structural applications due to manufacturing limitations [1–3]. However, recent new fiber extraction methods have been commercially developed to produce continuous long natural fibers with minimum damages induced to the technical properties of the fibers.

Numerous studies have confirmed that NFs (such as: hemp, flax, jute, etc.) are the most promising alternative of the man-made glass fibers when the mechanical properties per cost and weight comes into consideration [4–6]. Amongst the commonly studied NFs, flax fiber is recognized as one of the high performance NFs in terms of strength and stiffness per density, which makes it suitable for a number of structural applications [7–9]. In this regard, similar to man-made fibers, the NFs must be used in the form of continuous uni-directional (UD) or woven textile (with optimally twisted yarns) in the composite laminates so as to utilize the maximum load carrying capacity of the fibers [10,11]. However, one of the most concerned failure modes is interlaminar failure (namely delamination) in the laminated composites since there is no reinforcement in the thickness direction.

So far, investigations on the man-made composites have come up with various techniques, such as increasing the toughness of matrix, interleaving, engineering the interface adhesion between fiber and matrix, etc., to enhance the interlaminar strength of composites [12,13]. Through-the-thickness stitching of the fiber preforms has been acknowledged as a convenient and cost-effective technique for improving the interlaminar properties [14,15]. Consequently, a considerable amount of numerical studies have been devoted to model the interlaminar failure of the stitched man-made composite laminates [15–21].

Mai et al. [22] proposed two micro-mechanics based models to study the effects of stitching on delamination growth of laminate in double cantilever beam (DCB) specimen. In the first model, it was assumed that the stitches are not interconnected at the laminate surfaces, and in the second one, the effect of interconnected stitches was taken into account. The model provided a good understanding of the influence of stitch thread size on the delamination resistance. Sun et al. [17] used a 2-node nonlinear rod element with the micromechanical stitching models introduced in [22], and studied the effect of stitch distribution on improving the delamination resistance by means of virtual crack closure technique (VCCT). In this model, the stitch elements were located between 2 sub-laminates in which their initial length were zero (before any load was carried by the stitches) and it was assumed that only tension loads can be carried by the stitch elements.

Iwahori et al. [19] and Tan et al. [20] developed a 2-D finite element model to simulate the delamination propagation of stitched CFRP for the DCB test by using a 3-node rod element to represent a stitch thread. The authors also developed a novel test method to understand the mechanical progressive damage behavior of a single stitch thread (i.e. interfacial deboning, slack absorption, stitch fracture and frictional pull-out) as it is loaded in tension. The results of this test were used as a material model for
the stitch elements. The model gave good prediction of the experimental load-displacement curves and critical mode I strain energy release rates (SERR), $G_{IC}$.

This study aims to experimentally and numerically investigate the mode I interlaminar fracture toughness of stitched natural fiber composite laminates made from continuous UD flax fiber, epoxy polymer and twistless flax stitching yarns. A 3D Finite Element (FE) model of a DCB specimen was constructed using cohesive element with nonlinear softening law to model fiber bridging effect and embedded 2-node beam element for the stitch yarn, to simulate the Mode I delamination propagation in the stitched NF composite laminate.

**EXPERIMENTAL STUDY**

**Double Cantilever Beam (DCB) Test- Material and Specimen Preparation**

The experiments of this study were performed on the composite specimens made of 110g/m² unidirectional flax fibers (LINEO, Belgium) and thermoset resin system Epolam 5051 (Axson, France) with the layup of [0]$_{16}$. The composites were manufactured by the Vacuum Assisted Resin Infusion (VARI) technique.

A Tex 250 twist-less flax yarn (Composites Evolution, UK) was used to stitch the fiber preform at stitch row spacing of 4mm and stitch length of 12mm. To introduce a pre-crack, the front section of the preform was left unstitched to accommodate a 18μm thick polytetrafluoroethylene (PTFE) film insert as a crack starter. A schematic illustration of the stitched DCB specimen and the stitch configuration are shown in Figure 1.

The stitched and unstitched DCB test specimens with a dimension of 20mm by 170 mm by 4mm were cut from the composite panels. Unidirectional glass fiber reinforced thermoplastic tabs with an average thickness of 1 mm were bonded (with Scotch-Weld™ DP-420 Epoxy adhesive) to both arms of the DCB test specimens to prevent large deformation as well as failure of the specimens’ arms. Aluminum load blocks were then bonded to the arms of specimens as prescribed by ASTM D5528 [23]. All bonding surfaces were lightly polished, sand blasted and wiped with acetone-soaked cloth before application of adhesive.

The Mode I DCB tests were performed on an Instron 4505 universal testing machine equipped with a 1 kN load cell, at the cross-head speed of 1 mm/min. An initial loading-unloading cycle was performed to propagate the crack by 3 to 5 mm from the pre-crack (PTFE insert) so as to create a naturally sharp crack tip. Then, a second loading-unloading cycle was performed where to propagate the crack by about 60 mm. The crack propagation was monitored visually during the test by means of a travelling microscope and the crack length was recorded for every 1 mm of crack length increment.
The data reduction method of Modified Beam Theory (MBT), outlined in ASTM D5528, was applied to determine the critical mode I fracture energy release rate, $G_{lc}$, as:

$$G_I = \frac{3P \delta}{2b(a + |\Delta|)}$$  \hspace{1cm} (1)

where $P$ is the opening load, $\delta$ is the cross-head displacement of the test machine, $b$ is the specimen width, $a$ is the crack length, and $\Delta$ is the intercept of the plot of the cube root of the specimen compliance, $\delta/P$, against the crack length, $a$. According to the ASTM standard, the MBT method is recommended since it generally yields the most conservative values of $G_{lc}$.

**Evaluation of tensile properties of the impregnated stitch yarn**

The stitch yarn, as a through-the-thickness reinforcement of the composite, will experience tensile loading during the Mode I opening test. It was therefore necessary to evaluate the tensile properties of the flax yarn impregnated with resin. This information is needed to understand the stress-strain contribution of the stitch reinforcements when bridging a crack. The test specimens were prepared by infusing 25 cm long dry flax yarns with the same epoxy resin, Epolam 5015, via the VARI technique. The cured, impregnated yarns were tested at a gauge length of 10, 20 and 30 mm and the cross-head speed of 1 mm/min, using an Instron 5500 micro tester machine with a 1 KN load cell. The tensile tests were conducted on ten stitch yarn specimens to assess the variation of the tensile properties of the stitch yarn. The dry twist-less flax yarn and the tensile test set up for the resin impregnated yarn are shown in Figure 2.
MODELING OF INTERLAMINAR FAILURE IN UNSTITCHED FLAX FIBER COMPOSITE

Experimental DCB test results

The $G_{IC}$ values obtained from the DCB tests of the unstitched UD flax fiber composites in relation to the change in crack length, $\Delta a$, during crack propagation, are presented in Figure 3. In addition to the MBT method, the results determined from the Compliance Calibration (CC) and the Modified Compliance Calibration (MCC) methods [23] are also plotted to check for discrepancies in the calculation of $G_{IC}$ values through the use of different data reduction methods. It was observed that these three methods, which are all based on the relation of Irwin-Kies for SERR [24], led to a very similar $G_{IC}$ results with a maximum variation of 2.5%.

From the DCB test results of the unstitched flax composite, it was observed that the interlaminar fracture toughness rises steadily with increasing the crack (delamination) length as the crack propagated in steady-state. In general, such a response which is often referred to as the resistance curve or R-curve, indicates the involvement of different physical phenomena occurring in tandem during the fracture process. The R-curve association with fibre bridging is a well-established phenomenon [25] and the slow rise in fracture resistance of the flax/epoxy specimens up to the first peak $G_{IC}$ value at $\Delta a \approx 20-25$ mm (Figure 3) agrees well with our experimental observation of a large natural fiber bridging zone that measured up to 25-30 cm long when it was fully developed (Figure 4). In this case, the R-curve observed for the interlaminar fracture of the composite is therefore attributed to the increase in apparent stiffness and delamination resistance of the specimen as a result of fiber bridging.

This scale of fibre bridging is believed to be a unique characteristic of untwisted UD natural fibre composites, as the yarn architecture allows the elementary natural fibres to behave in the way similar to discontinuous aligned long fibers. The long bridging zone could also explain why the interlaminar fracture toughness of the flax composite is significantly higher than those measured for glass fiber composites (671 J/m²) [26]. It is therefore essential to consider the effect of fiber bridging in the FE delamination model for natural fiber composites, in order to achieve a more accurate prediction of their strength and fracture behavior.
The experimental results shows that the average initiation value of $G_{IC}$ for the UD flax/epoxy composite is 0.771 kJ/m$^2$ and the steady-state $G_{IC}$ value is 1.25 kJ/m$^2$ which is reached after approximately 25-30 mm of crack propagation. The length of crack propagation before the steady-state phase of critical SERR are estimated based on the mean value of the steady-state $G_{IC}$ with a 95% confidence interval (for upper and lower limit).

It has been established for synthetic fibre reinforced composites that Mode I delamination, which is assumed to happen in the homogeneous resin-rich region in-between fiber layers, can be modeled by bilinear traction-separation (cohesive) law [27]. However, this model is not able to represent the $G_{IC}$ R-curve when delamination is accompanied by extensive fiber bridging. To address this, several authors have shown that the traction-separation law with non-linear softening can be used to model the R-curve response as well as the enlarged process zone associated with crack bridging [28–31].

Figure 3. Experimental $G_{IC}$ values of two unstitched UD flax/epoxy composite calculated using the MBT, CC and MCC methods proposed under ASTM D5528 [31].
In this study, cohesive law with bilinear softening, which is being obtained from superposition of two linear softening law, is used to model the delamination crack propagation in the presence of fiber bridging. Semi-analytical approach proposed by Airoldi et al. [32] is applied to the DCB test results (R-curves) of the UD flax fiber composite to determine the parameters of the superposed cohesive laws.

Trilinear Cohesive Law for fiber bridging modeling

A Trilinear Cohesive Law (bilinear softening) obtained from superposing of two linear softening cohesive laws, is applied to model the fiber bridging effect encountered during Mode I fracture of UD flax fiber composites. Accordingly, a semi-analytical equation for extracting the superposition parameters of the cohesive laws from the experimentally obtained R-curves are used [32]. In this method, two bilinear cohesive laws with their own specific characteristics are superposed to obtain a trilinear cohesive law, as shown in Figure 5(a). The superposition parameters m and n are define as:

\[
G_1 = mG_c, \quad G_2 = (1 - m)G_c \\
\sigma_1 = n\sigma_c, \quad \sigma_2 = (1 - n)\sigma_c
\]

where \(\sigma\) and \(G\) refers to the cohesive strength and fracture toughness, respectively. According to this method, it is necessary to establish a relationship between the steady-state process zone in the presence of fiber bridging (superposition cohesive law), \(l_{p2,Sup}^{ss}\), and the characteristic length of each primary bilinear cohesive laws, \(l_{ci}, i = 1, 2\).

By applying this approach to the experimental R-curve (Figure 3), the superposition parameters m and n are calculated as \(m = 0.616\) and \(n = 0.9699\). The resultant trilinear cohesive law (using the obtained values of n and m) are applied to the cohesive elements of the FEM model of the DCB specimen.
FE model of the unstitched flax fiber composite

A DCB test specimen model with the fixed dimension of 6mm thickness, 20mm width and 62mm initial crack length was created using the commercial software Abaqus. Each arm of the specimen is comprised of two 8-node quadrilateral in-plane continuum shell elements (DC8R) through the thickness. These elements were used to model UD flax fiber composite as the inner layup, and UD glass fiber composite as the reinforcing tab on the outer face of each arm. The mid-section interlaminar layer where the two arms are joined is modeled by an 8-node three dimensional cohesive element (COH3D8) with the obtained trilinear cohesive law. The material properties of the flax fiber laminate and its interlaminar fracture toughness were obtained from the experimental results and the properties of the glass fiber laminates were adopted from literature. The elastic material properties used in the simulation of DCB test are given in Table 1. Figure 5(b) represents the FE model of the DCB specimen and the material of each section.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_1$ (GPa)</th>
<th>$E_2, E_3$ (GPa)</th>
<th>$\nu_{12}, \nu_{13}$</th>
<th>$\nu_{23}$</th>
<th>$G_{12}$ (GPa)</th>
<th>$G_{13}, G_{23}$ (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax fiber composite</td>
<td>18.55</td>
<td>1.5</td>
<td>0.29</td>
<td>0.3*</td>
<td>0.8*</td>
<td>0.6*</td>
</tr>
<tr>
<td>Glass fiber composite [33]</td>
<td>47.79</td>
<td>13.60</td>
<td>0.257</td>
<td>0.3</td>
<td>5.9</td>
<td>5.23</td>
</tr>
</tbody>
</table>

* Estimated values

The force-displacement response of the DCB test specimen model of unstitched UD flax fiber composite using bilinear and trilinear cohesive laws, and compared to the experimental data, are shown in Figure 6.

It can be clearly seen that the prediction with linear softening law is not suitable for modelling the interlaminar fracture of the UD natural fiber composite. When the initiation value of $G_{IC}$ was used (“Linear Softening ($G_{IC}=0.77$”), the overall force response is underestimated. Using the steady-state $G_{IC}$ value (“Linear Softening
(GIC=1.25)”) overestimates the failure loads in the early period of crack growth that most likely coincides with the development of the fiber bridging zone. These results thereby confirm that the use of linear softening law to model delamination in the presence of extensive fiber bridging (Figure 4), can introduce severe inaccuracy to the prediction of failure loads during DCB test.

Conversely, the use of trilinear cohesive law (“Bilinear Softening (GIC=1.25”)” gives a good approximation to the experimental load-displacement curve. The nonlinear softening law is able to predict the initiation of nonlinearity of the loading curve as well as the propagation portion very well. Generally, in the presence of fiber bridging, the damage process zone is extended by inducing bridging traction over the wake of the crack tip.

The experimental $G_{IC}$ R-curve is compared to the prediction results from the FE analysis in Figure 7. Once again, the trilinear law fits the initiation and the final steady-state values of experimental $G_{IC}$ very well. However, the experimental R-curve hits a peak $G_{IC}$ before reaching steady state propagation which is not predicted in the FE analysis results. This is because the trilinear cohesive law parameters of $m$ and $n$ were calculated based on the average steady-state $G_{IC}$ value of 1.25 kJ/m$^2$. As discussed previously, this value was chosen so as to cover a representative set of steady-state data points from the experimental R-curve. The trilinear cohesive law obtained by this method was then employed as the interlaminar response of the parent laminate to model the delamination of stitched laminates.

![Figure 6. Force-displacement response DCB test specimen of unstitched UD flax fiber composite; FEM & Experimental.](image-url)
MODELING OF INTERLAMINAR FAILURE IN STITCHED FLAX FIBER COMPOSITE

3D FE implementation of the stitch composite

To model the interlaminar fracture of the stitched UD flax fiber composite, the stitch elements were superposed with the cohesive element in the 3D FE model of the DCB specimen. The Abaqus 2-node beam elements (B31) representing the stitch elements were embedded within the cohesive element at a similar stitch density and distribution to the experimental DCB specimen (Figure 1).

The tensile test results of the impregnated flax yarns were used to define the properties of the beam element. It was assumed that the beam elements have a circular cross-section with a radius of 0.32 mm, exhibit brittle failure with negligible yield and carry tensile loads only. The value of $X_t = 18.9 \text{ GPa}$ and $E = 18.9 \text{ GPa}$ were used for the strength and modulus values of the beam element, respectively.

The trilinear cohesive law determined in the previous section was applied to the cohesive element. The schematic diagram of the fracture phenomenon involving fibre bridging and stitch pinning during crack opening and the corresponding 3D FEM model of the DCB test specimen with the embedded beam elements are shown in Figure 8.
FE Analysis results for the stitch composite

The force-displacement response of the numerical simulation of the stitched UD flax fiber composite are plotted against the experimental results in Figure 9. The experimental curves are intended to provide an indication of the unpredictability of the onset of the stick-slip crack propagation. As it can be seen, the FEM model shows reasonably good agreement with the experimental responses. Although the first stick-slip onset fracture point is different, the predicted response in terms of the peak and crack arresting loads as well as the linear behaviour of the load-displacement curve, are within the range of the experimental results. The slope is characteristic of DCB specimens due to the change in arm compliance as the effective arm length increases. The regularity of the stick-slip crack growth in both numerical and experimental results do suggest that the behavior is intrinsically linked to the strain energy build up and release events induced by the stitch reinforcements.

A number of explanations can be offered for the discrepancy between the experimental and predicted force-displacement response. First, it can be attributed to the variation in the stitch punching locations and distribution. In practice, actual stitch parameters (stitch length and row spacing) do deviate from the nominal values due to the unavoidable inaccuracies of hand-stitching. Second, some variation in thickness of the DCB specimen arms which can occur with the VARI manufacturing method can also lead to some variations in the linear response of the specimens (before crack initiation). Third, variation could also have arisen from the properties assigned to the stitch elements, as the consistency and properties of natural fibres can often vary by up to 25-30%. Despite these discrepancies, the predicted response is considered to be reasonably representative.
Figure 9. Force–displacement response of stitched DCB test specimen; Experimental and FEM analysis results.

Figure 10 compares the predicted critical SERR of the stitched DCB model with the experimental values of $G_{IC}$ with an identical stitch density. The stitch density, despite the inaccuracies of hand-stitching, is assumed to remain unchanged and it is therefore considered to be a common variable. The results shown in this figure indicate that the prediction of the stick-slip initiation $G_{IC}$ values by the FE model do give a reasonable representation of the experimental results for the stitched composites to within 25% accuracy. The virtual DCB test also exhibits the R-curve response, ramping from initiation $G_{IC} = 1.3 \text{ (kJ/m}^2\text{)}$ to the constant stick-slip propagation values of $G_{IC} = 2.265 \text{ (kJ/m}^2\text{)}$, which agree with the range of the experimental values to a fair degree. The average experimental values are $G_{IC} = 1.338 \text{ (kJ/m}^2\text{)}$ and $G_{IC} = 2.225 \text{ (kJ/m}^2\text{)}$ for initiation and stick-slip propagation respectively. It is now confirmed experimentally and with FE prediction that stitching with twist-less flax yarn can enhance the average interlaminar fracture toughness from $G_{IC} = 1.25 \text{ (kJ/m}^2\text{)}$ for unstitched laminates to $G_{IC} = 2.225 \text{ (kJ/m}^2\text{)}$ for the flax yarn stitched composites.
CONCLUSION

The effect of introducing out-of-plane flax fiber stitches on the Mode I interlaminar fracture toughness of the UD flax/epoxy composite laminates was experimentally and numerically investigated. The DCB test results for the unstitched flax fiber composites showed a strong R-curve effect which is attributed to the large-scale in-plane fiber bridging, observed during delamination advancement. The experimental findings also showed that the use of twist less flax yarn stitches was effective and can improve the critical SERR at by around 78% to over 2 kJ/m².

In numerical analysis, cohesive element with bilinear softening law obtained from superposition of two linear softening cohesive law was used to model the R-curve effect. This was superposed with beam elements as the stitch fibers to simulate the delamination of stitched laminate in the presence of extensive in-plane fiber bridging. The FE analysis results showed reasonably good agreement with the experimental results, and the prediction of the critical SERR for the initiation and propagation phase of delamination were within the range of the measured values. The results of this study suggests that stitching is a promising technique to enhance the interlaminar fracture toughness of flax/epoxy composite laminates, and it is crucial to consider the effects of in-plane fiber bridging to have an accurate prediction of $G_{IC}$ values for stitched natural fibre composites.
REFERENCES