KINK BANDS IN FLAX AND HEMP POLYESTER COMPOSITES

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1 Introduction

Natural fibre composites are a large area of interest in the academic community at present. The main problems that prevent their immediate use in structural applications are uncertainties associated with fatigue and shortfalls in mechanical properties [1]. Many of these shortfalls have been traced to fibre defects [1-4] including kink bands, which are folds or bends in the fibre walls, often induced in the extraction and handling process. When encapsulated in a matrix material, these kinked areas are reported to influence the Young's modulus and act as stress concentrations, especially in brittle matrices.

Kink bands are also a problem in traditional composites, including those manufactured from Kevlar fibres. In previous studies, a variety of polyester natural fibre composites were manufactured using a vacuum infusion process using both untreated and pre-treated fibres. From the trends observed during the mechanical testing and SEM, an understanding of how kink bands can affect the mechanical properties was gained. It is intended to combine these observations with those from the literature to provide more understanding of their influence in the materials.

2 Study Materials

In a study previously, a range of natural fibre composites were produced as shown in Fig. 1. Particular evidence was found in this study of the presence of kink bands in the flax and hemp composites. These composites were manufactured using a vacuum infusion process as shown in Fig. 2.

Fig. 1. Examples of the tested natural fibre composites, including flax and hemp

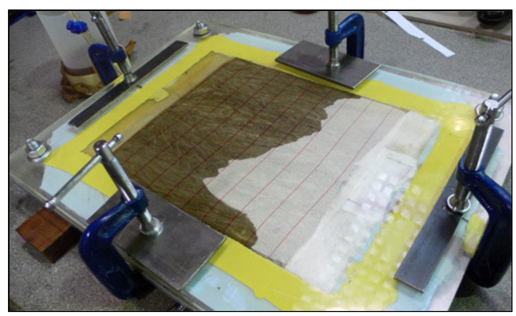

Fig. 2. Vacuum infusion rig for material manufacture

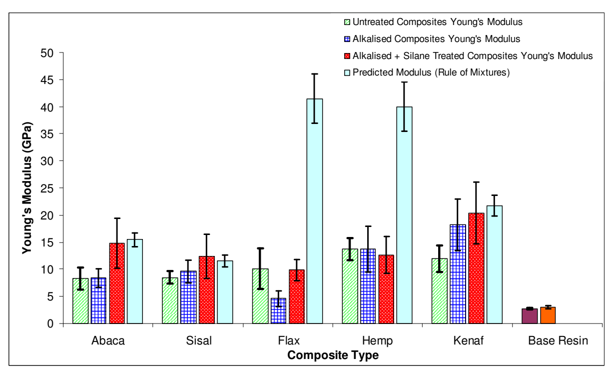

Fig. 3. Observed shortfall in flax and hemp composite modulus when compared using the rule of mixtures

In particular, Flax and Hemp composites had a severe shortfall in Young's modulus prediction using the 'rule of mixtures' as shown in Fig. 3. Investigations were conducted to further understand the root cause of this, and kink bands were consequently found throughout the fibres.

3 The Effects of Kink Banding

The following should be noted:

- Kink bands are often present in Flax fibres and significantly affect fibre properties including tensile strength and Young's modulus. Kink bands can also be introduced through the manufacturing process [1, 2].

- Kink bands can act as sites for fibre matrix de-bonding initiation as well as stress zones for initiating matrix micro cracking [1].

- Kink bands or similar defects are known to contribute to the non linear behaviour of fibres and resulting composites [4].

- The kinks may be thought of as areas of relatively lower stiffness and when the fibre is loaded the kink begins to extend [1].

In addition to these literature observations, a number of similar findings occurred within this work, including:

- From photomicrography and SEM, a large number of 'kink bands' or slip planes were observed throughout the flax and hemp fibres. Evidence of kink bands were also found in the flax and hemp fibre using luminescent light and are shown in Fig. 4 and 5 respectively. Fig. 6 shows one of many SEM images of a kink band at a resin break point.

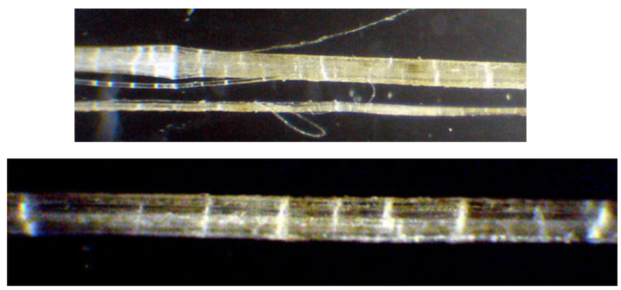

Fig 4. Kink banding evident in the flax fibres

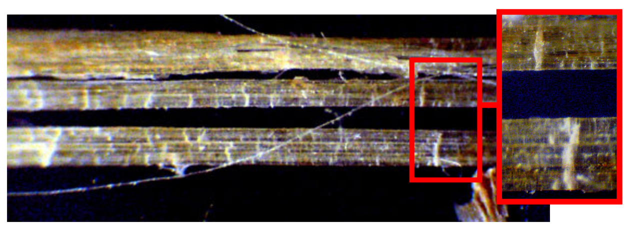

Fig. 5. Kink banding evident in the hemp fibres

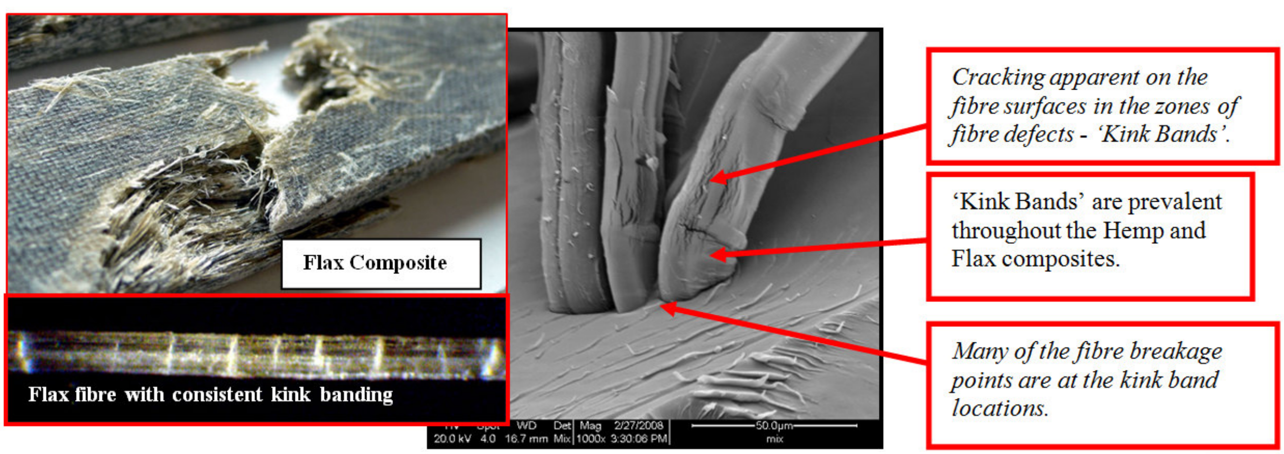

Fig. 6. Example of the numerous 'kink bands' observed in flax and hemp composites

- The Young's modulus for the flax and hemp composites in this study were far below predicted levels. The work conducted by Hughes et al. supports the suspicion that the kink bands are extending during loading, and thereby considerably lowering the Young's modulus [1]. Kink bands are also a problem in traditional composites, including those manufactured from Kevlar fibres. The kink bands reduce the tensile strength of these materials also.

- Fibre bundling is clearly observed in the SEM images obtained in this study, especially for the flax and hemp composites. It is thought that if the bundles are not penetrated with resin, the combined extension effect of the bundled kink banded fibres may be greater than in the individual kink banded fibres. The deformation behaviour of flax and hemp fibres displaying multiple defects is currently unknown, especially for bundles of the defected fibres. It is however intuitively thought that their combined stiffness will be less than a singular fibre with kink bands.

- From the SEM images of the kink bands fibre cracking and tearing is generally observed around the defects. It is also interesting to note, some of the kink bands emerge exactly on the matrix breakage points.

- The vacuum infusion process involves large compression of the natural fibre before infusion. This process may induce defects such as kink bands. Evidence to the true effect of the compression is not immediately apparent as studies revealed the base fibre was already heavily covered in kink banding.

When using the rule of mixtures to estimate composite modulus properties it is assumed that the natural fibres behave in a Hookean manner. Hughes et al. described the kink bands as regions of relatively lower stiffness, and when the fibres are initially loaded the defects begin to extend [1]. From previous studies, it is apparent that this effect is likely to be accurate, as fibres displaying kink bands still had high properties when the base mechanical fibre properties were tested. However, the variability in strength results was very high. It is evident that during load uptake of the flax and hemp base fibres that defects 'straighten' to a certain degree and act more like the traditional fibre cell wall and the fibre properties remain reasonably representative. This effect is not able to happen in the composite. In the composite the fibre is surrounded by a matrix material and the kink bands folded shape can mean they become 'locked' and act as stress concentrations during material loading. It is thought when kinked fibres are encapsulated in the matrix the fibres are likely to break at the stress concentrations in the area of these defects. If the fibres are thought of as segments joined by kink bands it would imply that behaviour would be similar to that of a short fibre composite. Due to the exceptionally low failure strengths exhibited with such a high fibre property, this hypothesis would seem reasonable. It may therefore be argued that the kink bands may be likened to 'end effects' experienced in short fibre composites, although it is likely the problem will be more complex.

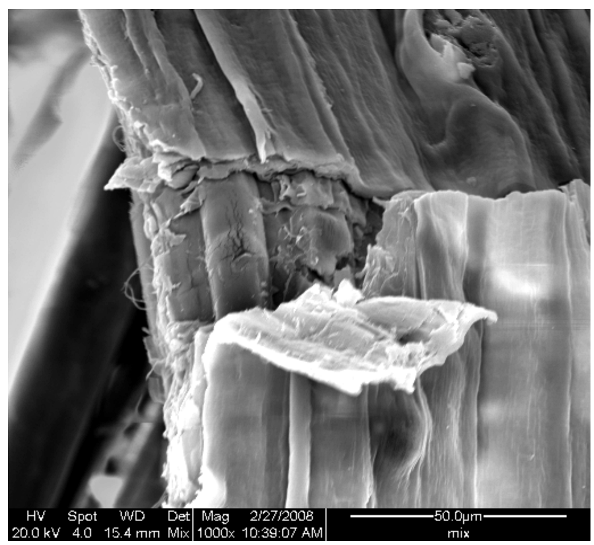

Fig 7. SEM image of the surface of an untreated Flax fibre in composite after testing, showing the fibre layers and complexity

Other issues relating to the shortfalls in composite stiffness can also be discussed. From the literature, it has been outlined that crack initiation is most likely at kink band locations. Therefore on the outer surfaces it may be speculated that the fibre outer layers (S1 layer) between defects are acting like 'segmented sleeves' around the central fibre core (S2 layer). The complex layering of the natural fibres contributes to the anisotropy of the fibre as shown in the transverse strengths, which is much lower than the longitudinal strength [5]. It is stipulated that this layering effect in combination with kink bands may reduce the effective stiffness of the fibre when embedded in the composite. When breakage occurs in the outer fibre walls and the kink band stress locations, the fibre properties at these concentrations may be more in the order of the fibre central core of the flax or hemp. Tearing of the outer wall of the flax fibre from a composite failure surface is shown in Fig 7. The stiffness of the inner sections of the flax and hemp fibre are not fully known, and therefore composite property predictions would be difficult.

4 Extension of Defects

When encapsulated in a resin matrix, a kink band in the fibre wall could be regarded as a defect, and consequently a stress concentration at the composite interface. When the composite is subject to load, the fibre, and hence defect is encouraged to extend, and this could be regarded as an 'extension of a defect'. From the study of Flax and Hemp polyester composites by Hughes et al. observed:

- Non-linear tensile behaviour, not just for the Flax fibre composites, but also for most of the natural fibre composites contained within.

- Reduction in strain to failure with improving interfacial bonding.

- Fibre treatments are generally lowering the strain to failure for the composites, and consequently affecting the work to fracture of the materials.

Hughes et al. also noted that after a certain loading point, permanent deformation has been imparted to their laminates. They suggested that this point is at the location in the loading curve where irreversible micro-structural events occur leading to what Hughes et al. suggested was the 'yield' point. The average yield stress was found to be in the region of 36 MPa, [1] which is in the early stage of the loading curve. The materials within our own study were also found to be highly non-linear, especially in the first stages of flax composite loading. This is where Hughes et al. suggest irreversible damage occurs in the loading curves. In the work enclosed it was also found that unusual uptake trends are evident in many of the composite materials, and may be related to the 'yield' point as described by the authors. It is thought kink bands are playing a role in this.

Additionally, work was conducted by Hughes et al. to investigate the threshold of the 'yield point' through the use of 'Acoustic Emission' analysis. It was found that during the suspected yielding point, the Acoustic Emissions picked up increased signals, which supports their suspicions of micro-mechanical damage at this location. In this study 'Acoustic Emissions' was not employed, however the early yielding point which Hughes et al. describes does seem apparent in some of the deformation curves, and not just for flax composites. It is thought that further investigations using this technique may be beneficial in future studies. If the composites are being internally damaged under low loadings, there are many unknowns as to the material reliability including fatigue life and resistance to external environmental conditions. Any micro-mechanical defects will accelerate failure during material usage. If it is found that damage is occurring at this early stage in the loading curve, this could have significant implications for the use of natural fibre composites in structural applications where fibre quality remains uncontrolled.

The observations of the early 'yield' point are interesting. Hughes et al. also experienced problems with kink banding in their work with the flax composites, and also stated they did not have the opportunity to investigate the tensile response of the individual base flax fibres. In the case of our own work, the tensile testing graphs are available from the base fibres. Using this information and analysing the stress-strain curves of the base flax fibres shown in Fig. 8, it is interesting to note that at the specified tensile strength of 32 MPa and failure strain of 0.12% where Hughes et al. report the 'yielding' approximately occurs is in the centre of an instability region of the flax fibres. Significant disruptions appear in the fibre structure before stabilising further on in the loading curve. It is thought that this region may be linked to the 'extension of defects' as described by Baley et al., where kink bands start to adjust and additionally the microstructure looks to align before taking the loading effectively. As the flax fibres are locked in a resin, the limited organisational ability of the fibres may promote early micro-mechanical damage in the composites and therefore could play a significant factor in hysteresis and inelastic effect relating to the composite yield point. From this point it is interesting to note, that many fibres have these instability regions. In Fig. 9 the instability regions of the base hemp fibres during initial loading is shown. This instability region shows similar trends to the flax fibres, which would suggest they may display similar yielding behaviour when processed into a composite. The failure strain of hemp and flax fibres are deemed to be in the region of 1.5 % and 2.5% respectively. With the instability regions from uptake in the fibres being in the order 0.06 – 0.16 % this presents a very small portion of strain to failure, and consequently the composites are finding it difficult to enter the true performance zone, due to the possibilities of the micro-mechanical damage highlighted by Hughes et al.

The base fibre instabilities from tensile testing are not limited to the bast fibres of flax and hemp where kink banding is observed. Kenaf and also abaca displayed this instability in fibre uptake to a lesser degree. However sisal fibres show more complex tensile instabilities during loading. This is likely due to the complex cycle of breakage, tearing and load transfer in the fibre cross section during loading. If unrecoverable damage is occurring in the fibres this may complicate composite use in structural applications, especially when under repeated loading. It should be noted however that the sisal fibres in this study responded well when processed into composites, and the results were close to those found by the rule of mixtures.

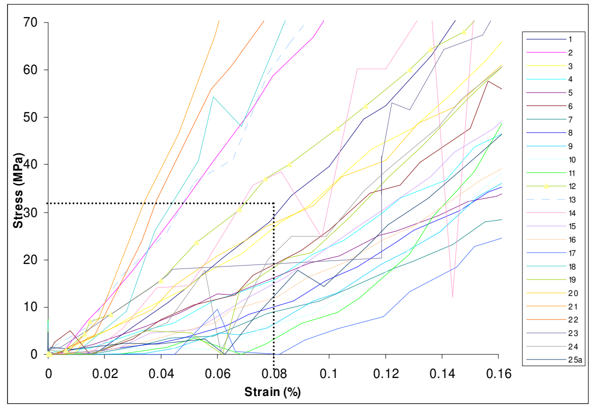

Fig. 8. Composite failure found to be in the region of the base fibre 'extension of defects' in flax fibre

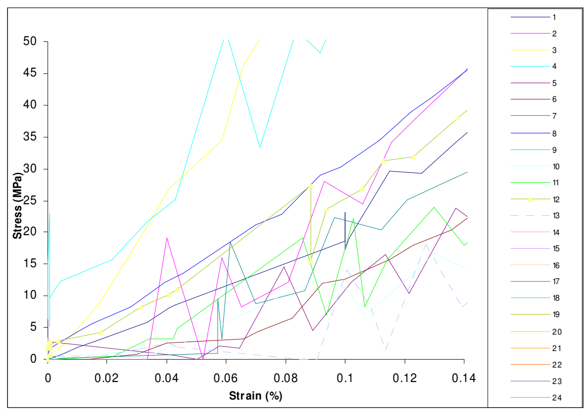

Fig. 9. Tensile test results of hemp fibre in the possible composite yield zone.

3 Study Conclusions

It may be appropriate to summaries explanations given in the previous discussion:

1. Strength reductions - Kinked fibres encapsulated in resin act as stress concentrations. These promote micro cracking of the matrix, fibre damage at these areas, and increase the likelihood of possible breakage. This behavior has been described as similar to short fibre composite with 'end effects' resulting in ultimate failure at low tensile strengths.

2. Stiffness reductions – Kink bands unravel to lower the overall stiffness of the composite. By the time true fibre uptake occurs within the deformation allowed at the interface, either cracking has initiated on the outer S1 layer of the fibre at the kink band or matrix failure has occurred in the polyester resin. Fibre 'bundles' complicate the issue, with the behavior of these kink banded fibre bundles acting in a manner not fully understood during composite loading.

The observations are additionally supported from the reasonable transverse mechanical properties in the flax and hemp composites during testing, where kink bands are less likely to affect the properties. This is due to the differing failure mechanisms dominating as opposed to the longitudinal direction, where kink bands have been shown to have the greatest influence. From these observation and discussions it is apparent that particularly in the case of flax and hemp composites, handling and methods during processing to avoid kink banding to the base fibres will improve the quality of the final materials.

Acknowledgements

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