Accepted Manuscript

Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form

J.M.F.A. Blanchard, A.J. Sobey, J.I.R. Blake

PII: S1359-8368(15)00526-0

DOI: 10.1016/j.compositesb.2015.08.086

Reference: JCOMB 3766

To appear in: *Composites Part B*

Received Date: 18 June 2015

Accepted Date: 31 August 2015

Please cite this article as: Blanchard JMFA, Sobey AJ, Blake JIR, Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form, *Composites Part B* (2015), doi: 10.1016/j.compositesb.2015.08.086.

Multi-scale investigation into the mechanical behaviour of flax in yarn, cloth and laminate form

Blanchard, J.M.F.A.[a,*], Sobey, A.J.[a] and Blake, J.I.R.[a]

[a]Fluid Structure Interactions Group, University of Southampton, United Kingdom, SO16 7QF

Abstract:

Due to environmental challenges it is important to investigate potentially more sustainable new materials, including natural fibre reinforced composites. Whilst a number of natural reinforcements show promise there is a concern that laminate properties are too difficult to predict due to the lack of uniformity in natural fibres. The paper quantitatively evaluates the high variability observed at yarn scale, at cloth scale, which shows significant decreases, and at laminate scale, showing comparable variability to synthetic based composites. This demonstrates that natural fibre reinforced composites have reproducible properties at the macroscale level and provides a pathway to application in industry.

Keywords: A. Yarn; A. Fabrics/ textiles; A. Laminates; B. Mechanical properties; Natural fibres

1. Introduction

Composite materials can have an adverse environmental impact. This is due both to the materials required to manufacture them and difficulties at end of life. An alternative not based on petroleum products, which are in short supply, is a new challenge of the 21st century. To mitigate these problems natural fibre composites are being investigated growing from an initial interest at the research scale to some early industrial implementations, in both primary and secondary structures.

Natural fibre composites present numerous ecological and economic advantages over standard composites including reported improvements in biodegradability, requiring less energy to be manufactured, reducing dependence on petrol and lowering pollutant emissions. The specific density advantage of natural fibres over glass allows for significant weight savings. When used in transport this can reduce operating costs and emissions as well as leading to energy and carbon credits from end-of-life incineration, as shown by

*Corresponding Address: Fluid Structure Interactions Group, University of Southampton, Boldrewood Campus, Burgess Road, Southampton, SO16 7QF, United Kingdom.
Tel: +44 2380 597773
Fax: +44 2380 597744
email: J.Blanchard@soton.ac.uk

Joshi et al. [1], Dicker et al. [2] and Yan et al. [3]. Furthermore, natural fibre composites use by-products, adding value to the agricultural sector as shown by Van Rijswijk et al. [4].

One perceived problem with natural composites is the variability at the fibre level due to climatic variation during growth and for fibres originating from different regions. As defined by Van Den Oever et al. [5] a natural fibre is made up of number of discontinuous elemental fibres that constitute a bundle. A number of bundles are assembled to form a yarn which are twilled into a cloth to construct a laminate. The variability of flax fibres starts with these elementary blocks which form a laminate.

The lack of general uptake in natural composites is at least partly due to the perceived variability in their mechanical properties, often measured at the coupon level, which impacts their candidature as structural materials. This is corroborated by Andersons et al. [6] who showed that natural fibres are affected by irregularities in growth leading to inconsistent fibre properties, around 30% variation in Young's Modulus and failure strain dependant on the fibre length, from growing in different areas.

There is an increasing body of literature to categorize the properties of natural composites and to show initial uses in industry. Joshi et al. [1] and Ho et al. [7] report that they have been successfully implemented in the automotive industry for low grade, non-structural, composite applications. Looking to the future Dicker et al. [2] provide an excellent review of natural composites attributes and links these to potential industrial applications for these materials. This link to industry is further facilitated by the Ashby-type materials screening charts presented by Shah [8] showing the advantages of natural fibre reinforced composite products in terms of high tensile stiffness per unit cost and eco-impact. A few early applications of natural composites used for structural components are also presented. Shah et al. [9] compared two small wind turbines made of glass fibre and flax fibre reinforced composites and demonstrated that wind turbines made from flax fibres are a potential replacement to glass fibres as they satisfy the necessary structural requirements for a lower weight. Blake and Sobey [10] report that a high performance sailing dinghy sandwich hull and deck has been successfully built using flax fibres, a bio sourced resin and cork. A trimaran "Gwalaz" made from flax fibre, balsa wood, cork core and a 30% bio sourced resin built by Kairos, conceived in collaboration with IFREMER and LIMAT B completed a sailing tour around Britanny [11].

Some progress has been made into the categorisation of natural fibre reinforced composites for reliability purposes. Andersons et al. [6] [12] tested two types of flax and have demonstrated that the fibre ultimate strain follows a Weibull distribution and derived a fibre strength distribution function. Aslan et al. [13]

and Thomasson et al. [14] have studied the influence of the cross sectional area of single flax fibres and technical fibres, and concluded that they were not circular or uniform. It is also shown that a simple diameter measurement was not sufficient as the diameter is not uniform along the fibre length. To counteract these errors Virk et al. [15] considered the statistical variation in strain and strength for experimental data from 785 jute fibres and found that the failure strain is a more consistent failure criterion for natural fibre as it is independent of the cross sectional area measurement that can lead to inaccuracy.

Pan [16] evaluated a model utilising a new approach for calculating the critical yarn length to define fabric strength under uniaxial and biaxial extensions. This early work was added to by Andersons et al. [17] who showed that a Weibull analysis was the most appropriate for estimating strain and strength characteristics. Charlet and Beakou [18] studied the mechanical properties of interfaces within a flax bundle stressing the importance of separating the elementary fibres as much as possible from the bundles in order to increase the fibre-matrix interface and to decrease the fibre to fibre interface. Baets et al. [19] investigated the effect of the yarn twist angle and its effect on the unidirectional composites properties. The dry yarn strength improved as the twist angle increased but at the composite scale this was reversed and higher twist angles led to lower mechanical properties. Chabba and Netravali [20] tested 20 flax yarns in tension; the diameter was measured three times along the length to determine the cross-sectional area. The yarn's tensile properties are highly variable and it can be attributed to the measurement techniques used for the cross-sectional area. Madsen et al. [21] have characterized two batches of hemp yarns, sample size of 10, and found that the yarn‘s apparent stiffness is below that reported for single hemp fibres. However the yarn's ultimate stress is within the range reported for single hemp fibres. Xue and Hu [22] compared the mechanical properties of treated and untreated flax yarns, reinforcements and composites to study the effect of alkali treatment and found that laminate properties were improved by the treatment even though the mechanical properties at yarn and cloth scales were reduced. Munikenche Gowda et al. [23] tested the tensile strength of 5 yarns, fabric and polyester reinforced jute specimens. The results were compared to laminate results predicted from the rule of mixtures based on the yarn data where the yarn modulus was based on a circular assumption.

To relate the material properties of the fibre to the final laminate properties Virk et al. [24] considered the influences of the fibre length distribution; the fibre cross-section, the fibre orientation, and the fibre diameter distribution on the composite mechanical properties using a modification of the rule of mixtures.

It validates a novel methodology for the prediction of the tensile modulus, using the relation between measured and actual cross sectional area, and strength of natural fibre composites with considerations for each of the parameters in the rule of mixture based on statistical variation inherent in natural reinforcements. Charlet et al. [25] compared flax reinforced composites mechanical properties with those of elemental fibres. Flax bundle properties were then derived from available composite data and compared to the elemental fibres. It was found that the use of bundles as reinforcement, rather than elemental fibres, might explain the low composite mechanical properties compared with those expected from elemental fibre results. Andersons et al. [26] investigated the interface between flax bundles and vinylester resin and found that the mechanical interlocking and friction were assumed as the principal mechanisms of the apparent adhesion in the composite. Summerscales et al. [27, 28 and 29] made an extensive review of the literature related to natural composites from the beginnings of the growth stage, through material properties to methods for modelling the materials themselves. This work was complemented by Yan et al. [3] who conducted an extensive review of flax fibres and its composites and concluded that flax fibres had greater variability compared to synthetic fibres but despite this flax fibre reinforced composites have the potential to replace glass fibre reinforced composites for structural applications in the automotive industry.

Natural fibre composites are a promising replacement for standard composites for structural components. However, for industrial applications a greater understanding is required of their material properties and their manufacturability to allow design and production engineers to best design and build structures. This involves the modelling of composite mechanical deformations based on the properties of each of its constituents. The steps between elemental fibres and a bundle will not be investigated as this has already been widely studied in the literature, for example Aslan et al. [13], Andersons et al. [6], and Thomasson et al. [14]. However, there is a lack of literature investigating natural composites at a larger scale and so the smallest scale studied will be limited to the yarn. The aim of this paper is to investigate the influence of natural fibre variability on the composite and define how the overall structural performance is affected based on variability at different levels: yarn, cloth and laminate.

2. Experimental methodology

The general literature illustrates a number of different natural fibres which can be used for reinforcement purposes. This research is based on flax fibres combined with an epoxy resin. The flax fibres have been chosen for their good mechanical properties, low density and wide availability in Europe as reported by Charlet and Beakou [18], Codispoti et al. [30] and Gobi Kannan et al. [31]. Whilst there are some natural

resins available, epoxy was selected due to its well-known mechanical properties which allows focus on the variability of the fibre reinforcement, helping to isolate the uncertainty in the fibres' properties. Flax fibres from a single batch will be used for the majority of the study with a second batch used to record the load and displacement of the cloth. A woven balanced cloth (0/90°), "FlaxPly", described in table 1, made by LINEO in Belgium will be used throughout the study and the matrix is composed of a Gurit Prime 20 LV Epoxy resin.

2.1. Yarn experiments

2.1.1. Linear density

The linear density, defined for a yarn as the mass of a 1000 m length, is required to calculate the breaking strength. 121 yarns, from an initial length of 600 mm, have been weighed, before being tensile tested, to determine the linear density for the tensile testing using a Mettler AE 240 scale with a precision of 10^{-4}g. The variability of the linear density along the yarn has also been determined by weighing 100 yarns of 1cm length, using the same procedure as for the tensile test, to be able to determine a statistical distribution for the yarn's linear density. Yarns have been separated with care from the woven cloth and both transverse and longitudinal yarns have been tested.

2.1.2. Cross sectional area determination

To determine the stress in the yarn, the cross sectional area must be measured. This was performed using an Olympus microscope BX41M-LED. In order to make accurate observations, 100 yarn specimens have been embedded into an epoxy matrix. Each yarn was then polished using progressively finer grit, 120-1200. The angle between the yarn and the observed surface was measured and specimens not perpendicular to the surface were discarded. The cross sectional area of the yarn was observed at a magnification of 20. The images obtained have been transferred into the Image J software which was automatically calibrated against measurements from an objective micrometer. Whilst the shape of a yarn cross section is less variable than the elements of which it is composed it is not assumed to be circular [14]. After comparison of the images obtained from the yarns the cross sectional area is better considered as an ellipse and has been compared to the Image J freehand tool which gives an accurate result as it follows the yarn cross-sectional area exactly. As no accurate non-destructive method has been found to determine the cross sectional area of a yarn before testing, and the cross sectional area varies along the yarn in the same proportion as between different yarns, an average cross sectional area was used for the stress calculations based on these measurements. The breaking strength calculated with the linear density is more accurate than the breaking stress calculated with the cross sectional area as the linear density was

determined for each specimen before being tested. Comparing the techniques the breaking strength calculated with the linear density gave a coefficient of variation of 16 % compared to 20% for the tensile breaking stress, based on the averaged cross sectional area. This method is therefore reasonably accurate.

2.1.3. Tensile test

In order to obtain the tensile mechanical properties of a yarn, 95 specimens have been tested in tension according to BS ISO 3341:2000 [32] using an Instron 5569 with a load cell of 2kN. The yarns have been tested at a rate of 200 mm/min ± 20 mm/min using radiused clamps and a gauge length of 500 mm. The breaking strength calculated as the tensile breaking force per unit linear density of the unstrained specimen, was measured according to BS ISO 3341:2000 [32]. The tensile modulus was calculated between strains of ε_1, 0.09 %, and ε_2, 0.46 %, corresponding to part of the linear elastic region. These values have been determined by scaling the strains used to calculate the composite tensile modulus to the inverse of the averaged breaking strain of flax reinforced composites and yarns; where the composite tensile modulus is calculated between strains, ε_1, 0.05 % and ε_2, 0.25 %, as referred to in the ISO standards BS EN ISO 527-1:2012 [33].

2.2. Cloth

2.2.1. Cloth density

The properties at the cloth scale were studied and linked to the yarn's properties. The flax fibre used in this analysis has a manufacturer specified cloth density of 222.1 g/m^2. However, to obtain a more accurate result, a 10 cm x 10 cm cloth sample has been cut, by hand, and split into 100 specimens of 1cm^2, which have been used to evaluate the variability in the cloth density.

2.2.2. Tensile test

Following the density determination 20 specimens of cloth have been tested in tension to determine the tensile breaking force according to BS ISO 3342:2011 [34]. Less cloth specimens have been tested as the variability at this scale was considered to be less important having seen the reduction at laminate level. However it is important to investigate the properties that link the yarns results to the laminate. The specimens have been tested using an Instron 5569 machine at a rate of 200 mm/min ± 10 mm/min with a 50 kN load cell. The specimen's dimensions were 1300 mm long and 75 mm wide. To avoid slippage problems a standard length could not be used. Radiused clamps were used instead of the flat clamps described in the standard. Furthermore, to prevent the specimen slipping within the clamps, each end of the specimen had to be covered with a thick layer of tape which was assumed to have no effect on the

final results. Load and extension have been recorded but the gauge length could not be accurately determined due to the utilization of the radiused clamps.

2.2.3. Number of yarns per specimens

The number of yarns in each tested specimen of 75 mm was counted by eye to determine the correlation between the yarns breaking force and the cloth breaking force. The number of longitudinal yarns was counted at either end of the cloth specimen 22.0 cm from the edge, a distance corresponding to the end of the gauge length, and an average calculated for each specimen.

2.3. Coupon

7 identical panels of 8 layers of "FlaxPly"/Epoxy composite have been manufactured in the same conditions (pressure, temperature and humidity) to test the laminate material properties. Resin infusion was preferred for good mechanical properties and consistent properties across the plate. Whilst other methods provide a higher fibre volume fraction resin infusion is widely used in industry for natural fibre reinforced composites as a good compromise between the quality and cost [7][30][35]. The infusion process was followed by vacuum consolidation for at least 8 hours, and a cure time at ambient temperature of 24 hours. Panels were then placed in the oven for post curing for 16 hours at 50 °C, as recommended by the resin supplier, to improve mechanical properties.

2.3.1. Fibre volume fraction determination

The fibre volume fraction was defined by the constituent weights assuming no void content. Whilst this introduces some variation and uncertainty it was assumed that this would be minimal across the specimens, due to systematic variation, reducing the effects on the material properties and most importantly allowing reasonable data to be gained across the specimens. Each specimen was measured and weighed using a Mettler AE 240 scale before the tensile test, and the dimensions are based on a mean value calculated from 3 measurements for each specimen and dimension.

2.3.2. Tensile test

95 specimens, with no end tabs, have been tested according to the Standard BS EN ISO 527-4:1997 [36] using an Instron 5569 machine with a 50kN load cell. The specimens were on average 25.32 mm wide (CoV =1.84 %), 249.8 mm long (CoV = 0.49 %) determined with Vernier callipers, and on average were 4.31 mm thick measured with a micrometer. The breaking strength, breaking strain and Young's modulus have been determined according to the standard.

3. Multi scale material properties results

The experimental results found during testing of yarns, cloths and laminates will be presented in the following sections. These results will permit a better understanding of the relation between the yarn, cloth and laminate levels. The results for the densities, cross sectional areas and tensile strengths are presented alongside the distributions for these properties. Flexural properties for the laminate level are also included.

3.1. Yarns

3.1.1. Linear density

The mass and linear density values' for 121 specimens cut into 600mm and weighed and the results for the 100 yarns (length: 1cm) are summarised in Table 2. The linear density within the yarn is more highly variable for the shorter length, with a coefficient of variation of 25 %, compared to the linear density of the 600 mm yarns, COV of 13%.This is assumed to be a combination of the inaccuracy created from cutting the specimens into small sections and of the density variation along the yarn length with the larger value being more representative of the actual variation in fibre fineness. The experimental results are higher compared to the value given by the manufacturer; the difference can be explained by the smaller size of the specimens and the treatment applied on the yarns.

3.1.2. Cross sectional area determination

The cross sectional area was calculated based on measurements of 100 yarns. The variables associated with the freehand tool Image J software and the cross sectional area based on the elliptical and circular formula are compared in Table 3 with a representational microscopic image of a typical yarn cross-sectional area presented in figure 1.

The cross sectional area calculated using the freehand tool is deemed more accurate as it follows the exact shape of the cross section. The mean results using the elliptical estimate are within 11% of the freehand tool results, conservatively underestimating the cross sectional area by a small mean value. The circular formula's mean value based on the minor diameter is further from the freehand tool results underestimating the cross-sectional area by 21% whereas the circular formula's mean value based on the major diameter overestimates the cross-sectional area by 14 %. The circular formula's mean value based on the mean diameter is underestimating the cross-sectional area by 4%. This large variability between the circular formula based on the minor, major, or mean diameter shows that a single measurement of the diameter is not reliable. The coefficient of variation demonstrates that the fibre measurement using the freehand tool has a 24% variation about the mean and the elliptical formula has a variation of 27% about the mean whereas the circular methods create a greater variability as shown in Table 3. The elliptical

approximation has a smaller variation with a closer mean value and is considered to be a more suitable alternative to estimating the cross-sectional properties.

3.1.3. Tensile test

The stress and strain have been calculated using the load and extension recorded during the experiments with the cross sectional area data already recorded. The stress-strain curves calculated for the 95 specimens tested is shown in Figure 2, where it is possible to see that the stress-strain curve of a yarn first shows a short non-linear region corresponding to the rearrangements of the individual fibres within the yarns followed by a linear elastic section until yield point where the maximum force is taken. Some specimens exhibit a yield point followed by non-linear deformation before the final breaking point. This region corresponds to random damages, fibre variation or twisting angle rearrangements within the yarn. Similar behaviours have been reported for flax yarns by Xue and Hue [22] and flax tows by Moothoo et al. [37]. The curves show a high variability in the yarn's mechanical properties in terms of breaking elongation and breaking stress. The mean values for the mechanical properties are summarized in Table 4.

The weakest yarn breaks at a load of 11.6 N and the strongest at 34.1 N showing that the flax yarns are exhibiting a high variability, as expected. The statistical distribution of the yarn's tensile modulus is presented in figure 3. The experimental data can be assumed to follow a normal distribution with a confidence of 95 % as shown by the chi-square test value, $\chi^2 = 3.9728$, which is smaller than the critical value of $\alpha=0.05$: $\chi^2 = 15.507$. [38]

Whilst it is assumed that the high variability from the yarns comes from the variation in the material, the yarns tested have to be separated from the cloth and, even if the manipulation is performed with great care, it is possible that yarns may be damaged during the process. Prior damage may have occurred in the manufacturing process or these yarns contain elemental fibres that have been damaged during growth. The yarns also suffer from variability in cross sectional area and using the mean value may have an effect on the stress calculation. The variability in the yarns' fineness (Table 2) is lower than found in the tensile mechanical properties. The combination of the variability in the cross sectional area and the yarn's linear density can explain part of this but it appears that mechanical properties of the elemental fibres still have an important influence at the yarn scale.

3.2. Cloth

3.2.1. Cloth density

The values found from weighing 100 specimens of cloth are summarized in Table 5. The results show that there is a large difference in the coefficients of variation for the yarn's linear density, 25%, and for the cloth's, 8%. The cloth density given by the manufacturer is 222.1 g/m^2 and the mean value found for the cloth density is 283 ± 23.9 g/m^2. The value found by experimentation will be used for the calculations of the fibre weight fraction. Differences between the manufacturer value and calculated value might be explained by the small size of the specimens tested and also the coating applied by the manufacturer on the fibres.

3.2.2. Tensile test

As explained in the methodology, the breaking force was found from the cloth tensile test. The load-extension curves for the 20 specimens tested are shown in Figure 4. The load-elongation curve is once again not linear at the start of testing. As the yarn tensile testing progresses the cloth extends and changes the organization of the yarns breaking into a wave pattern within the gauge length. The cloth starts to break at the weakest point and the stress propagates from here. The starting point for the break was not the same for each specimen but can be seen to always be in the middle of the gauge length. Table 6 summarizes the results for the tensile breaking force.

The cloth breaking load variation is much smaller than that found for the yarn tensile test. The coefficient of variation for the yarn breaking force is 20% and 4% for the cloth. This difference can be explained by the fact that even if a few weak yarns are present in a cloth specimen, the load is carried by the adjacent yarns and does not dramatically change the mechanical properties. It is assumed that the difference in terms of variability between the linear density of the yarn, which is high, and cloth, which is lower, can be related to the differences found in the mechanical properties. The number of cloth specimens tested is considerably smaller compared to the number of yarn specimens tested which can influence the coefficient of variation.

3.2.3. Number of yarns per specimens

To investigate the correlation between the yarn and cloth mechanical properties, tests were performed to determine the number of yarns per specimen. For each specimen there was a mean of 71.6 with a maximum of 74 and a minimum of 69 yarns found from 20 specimens at 2 separate locations. This shows that the variability between the specimens was relatively low which helps to explain, together with the variability in density, the variation in the cloth tensile properties.

An approximation for the relation between cloth and yarns can be calculated from the breaking load of the cloth divided by the number of yarns in a specimen. The mean value for the cloth breaking load is 1491 ± 62.4 N. Assuming that only the longitudinal yarns are carrying a load during tensile testing, the load carried by each yarn is 21N. The mean value for the tensile breaking force found from the yarn tensile test is 22.6 ± 4.59 N. This approximation shows that the transverse yarns are not carrying any significant load. A potential hypothesis is that the difference in load is approximately equal to the friction caused at the yarn-yarn intersection and the weaving effect.

3.3. Laminate

3.3.1. Fibre volume fraction determination

The fibre volume fraction is determined. The cloth density was presumed from testing to be 283 ± 23.9 g/m^2, the flax density was assumed to be 1450 kg/m^3 [39] and the matrix density equal to 1089 kg/m^3 [40].

The mean values calculated for the fibre weight and volume fractions, based on 95 specimens from 7 different plates, are detailed in Table 7. The mean fibre volume fraction is 37.24 ± 1.8 %; it has been calculated assuming no void content and so the obtained result is a non-conservative estimate. The value is low compared to that expected for glass fibre reinforced composites manufactured with resin infusion, for example ISO 12215-5 advises a value of 58 % [41]. This was expected due to the current difficulties with infusing natural fibres. This result of 37.24 % is comparable to the fibre volume fraction seen in resin infusion for UD flax fibre reinforced epoxy composites for example the value of 40% found by Van de Weyenberg et al. [39]. Shah et al. [42] have found that the absolute limit of the fibre volume fraction of a natural fibre composite with twisted yarns is 58.9 % which is a theoretical hard limit and is unobtainable using the resin infusion process.

3.3.2. Tensile test

The stress-strain curve for the 95 specimens tested in tension is shown in Figure 5. The stress-strain curves can be considered to be linear elastic before brittle failure occurs. For a few specimens the stress-strain curves show a first non-linear region at the beginning of the test with the potential that the fibres are slipping over each other until they straighten. The variability in stress-strain curve seen at yarn scale is considerably reduced in the laminate. The tensile properties of the specimens are detailed in Table 8.

The mean breaking strength is 90.9 ± 7.18 MPa, the Young's modulus is 8.18 ± 0.42 GPa and the coefficient of variation for the breaking strength is lower than seen at the yarn level, 7.89%. This Young's

modulus is low compared to glass fibre reinforced composites but has a comparative level of variation, 5.08%, compared to the variability from Sriramula and Chryssanthopoulos [43] which is between 1 and 10 % depending on the manufacturing process. The flexural properties have also been determined for comparison. Based on 29 specimens, tested according to standard ASTM D 7264/D7264M-07 [44] with a span to thickness ratio of 20:1 the flexural modulus is 6.13 ± 0.37 GPa and the maximum flexural strength is equal to 114.91 ± 4.93 MPa. Flax fibre reinforced composites tested have lower flexural and tensile properties than woven glass fibre reinforced composites manufactured with resin infusion process from the literature [41, 45 and 46]. The fibre volume fraction for woven glass fibre reinforced composites is generally higher, 58 % [41], and this difference can explain the lower mechanical properties of flax fibre reinforced composites.

The mechanical properties of flax fibre reinforced composite are encouraging and the low variability compared to the yarn stage shows an increase in the reliability of the composite at the laminate stage giving comparative reliability to E-glass.

4. Discussion

The scope of work can be broadly divided into the following categories:

- The determination of flax fibre yarn, cloth and laminate mechanical properties by experimental testing.
- The influence of the yarn variability on the laminate mechanical properties.
- Investigation into the calculation of cross sectional area of yarns with different assumptions for decreased variability in the mechanical properties.

Research conducted into natural fibres demonstrates that the elemental fibres mechanical properties are variable and an obstacle to the utilisation of the natural fibre reinforced composites for structural components. To estimate the influence of the yarn variability on the composite mechanical properties the cloth breaking load has been determined. It has been shown that the breaking load of the cloth is broadly equal to the average breaking load of a yarn multiplied by the number of yarns in a cloth specimen and that the variability in cloth specimens is considerably reduced compared to the variability at the yarn stage. Current opinion, such as those reported by Dicker et al. [2], highlights that natural fibres exhibit high variability but the results shown here demonstrate that, at the laminate scale, this variability is not significantly higher than other composite materials already used for structural applications. The fibre volume fraction is low compared to standard composites manufactured using resin infusion and any

improvement will increase the mechanical properties, though the fibre volume fraction obtained for these experiments was similar to the value obtained by Van de Weyenberg et al. [39]. This indicates that further research into the production methods for flax reinforced composites must be investigated. It should still be underlined that the tensile modulus, 8 GPa, and flexural modulus, 6 GPa, show that the stiffness of the composite is low. This low modulus is partially caused by the high breaking strain of the composite but is counteracted, to some extent, by the high thickness of the plies increasing the flexural rigidity of the material.

It has been shown that the yarn cross-sectional area cannot be assumed to be circular and leads to inaccuracy in the calculations of the final mechanical properties. The elliptical estimate tends to underestimate the cross sectional area by 11% but shows a similar coefficient of variation compared to the true cross sectional area based on the freehand tool measurement. The circular estimates are highly influenced by the diameter used for the calculations but always show a higher variability. The elliptical estimate can therefore be used to predict the properties more reliably.

5. Conclusion

This paper has summarised experiments at the yarn, cloth and laminate levels of a flax reinforced composite material. The results permit a better understanding of the influence of the flax fibres variability on the final composite's mechanical properties by testing each scale from yarn to cloth and finally laminate. At the yarn stage, the variability in terms of tensile properties is large and explains the lack of confidence given to flax fibres for structural composites. The variability is reduced at the cloth stage and at the laminate level the variability is similar to that found within E-glass reinforced composites. It is also shown that the prediction of flax fibre reinforced composite properties can be improved, in scenarios with limited experimental budget, by considering the shape of the fibre to be elliptical.

Acknowledgments

The research is kindly sponsored by the Lloyd's Register Foundation (LRF).

References

1. Joshi SV, Drzal LT, Mohanty AK, Arora S. Are natural fiber composites environmentally superior to glass fiber reinforced composites?. Compos Part A-Appl S 2004; 35: 371-376.
2. Dicker MPM, Duckworth PF, Baker AB, Francois G, Hazzard MK. Green composites: A review of material attributes and complementary applications, Compos Part A-Appl S 2014; 56: 280-289.
3. Yan L. Chouw N, Jayaraman K. Flax fibre and its composites – A review. Compos Part B-Eng 2014; 56: 296-317.
4. Van Rijswijk, K., Brouwer, W.D. and Beukers, A., 2003, Application of Natural Fibre Composites in the Development of Rural Societies, Food and Agricultural Organization of the United Nations.
5. Van Den Oever MJA, Bos HL, Van Kemenade MJJM. Influence of the Physical Structure of Flax Fibres on the Mechanical Properties of Flax Fibre Reinforced Polypropylene Composites. Appl Compos Mater 2000; 7: 387-402.
6. Andersons J, Porike E, Sparnins E. Ultimate strain and deformability of elementary flax fibres. J Strain Anal Eng 2011; 46: 428-435.
7. Ho MP, Wang H, Lee JH, Ho CK, Lau KT, Leng J, Hui D. Critical factors on manufacturing processes of natural fibre composites. Compos Part B-Eng 2012; 43: 3549-3562.
8. Shah DU. Natural fibre composites: Comprehensive Ashby-type materials selection charts. Mater Design 2014; 62: 21-31.
9. Shah DU, Schubel PJ, Clifford MJ. Can flax replace E-glass in structural composites? A small wind turbine blade case study. Compos Part B-Eng 2013; 52: 172-181.
10. Blake JIR, Sobey AJ. Natural resourcefulness. Ship and boat international May/June 2013.
11. http://wwz.ifremer.fr/L-institut/Actualites/Archives/2013/Le-Gwalaz-a-boucle-son-premier-tour-de-Bretagne.-Des-champs-aux-oceans-un-grand-pas-pour-les-biomateriaux [Online] [cited: 10 August 2014]
12. Andersons J, Porike E, Spamins E. The effect of mechanical defects on the strength distribution of elementary flax fibre. Compos Sci Technol 2005; 65: 693-702.
13. Aslan M, Chinga-Carrasco G, Sorensen BF, Madsen B. Strength variability of single flax fibres. J Mater Sci 2011; 46: 6344-6354.
14. Thomasson JL, Carruthers J, Kelly J, Johnson G. Fibre-cross-section determination and variability in sisal and flax and its effects on fibre performance characterisation. Compos Sci Technol 2011; 71: 1008-1015.
15. Virk AS, Wayne H, Summerscales J. Failure strain as the key design criterion for fracture of natural fibre composites. Compos Sci Technol 2010; 70: 995-999.
16. Pan N. Analysis of woven fabric strengths: prediction of fabric strength under uniaxial and biaxial extensions. Compos Sci Technol 1996; 56: 311-327.
17. Andersons J, Sparnins E, Joffe R, Wallström L. Strength distribution of elementary flax fibres, Compos Sci Technol 2005; 65: 693-702.
18. Charlet K, Béakou A. Mechanical properties of interfaces within a flax bundle-Part 1: Experimental analysis. Int J Adhes Adhes 2011; 31: 875-881.

19. Baets J, Plastria D, Ivens J, Verpoest I. Determination of the optimal flax fibre preparation for use in unidirectional flax-epoxy composites. J Reinf Plast Comp 2014; 00:1-10.
20. Chabba S, Netravali AN. 'Green' composites Part 2: Characterization of flax yarn and glutaraldehyde/poly(vinyl alcohol) modified soy protein concentrate composites. J Mater Sci 2005; 40: 6275-6282.
21. Madsen B, Hoffmeyer P, Thomsen AB, Lilholt H. Hemp yarn reinforced composites - I. Yarn characteristics. Compos Part A-Appl S 2007; 38: 2194-2203.
22. Xue D, Hu H. Mechanical properties of biaxial weft-knitted flax composites. Mater Design 2013; 46: 264-269.
23. Munikenche Gowda T, Naidu ACB, Chhaya R. Some mechanical properties of untreated jute fabric-reinforced polyester composites. Compos Part A-Appl S 1999; 30: 277-284.
24. Virk AS, Hall W, Summerscales J. Modulus and Strength Prediction for natural fibre composites. J Mater Sci Technol 2012; 28: 864-871.
25. Charlet K, Jernot JP, Gomina M, Bizet L, Bréard J. Mechanical Properties of Flax Fibers and of the Derived Unidirectional Composites. J Compos Mater 2010; 44: 2887-2896.
26. Andersons J, Joffe R, Sparnins E. Evaluation of interfacial shear strength by tensile tests of impregnated flax fiber yarns. J Compos Mater 2012; 46: 351-357.
27. Summerscales J, Dissanayake N, Virk A, Hall W. A review of bast fibres and their composites. Part 1-Fibres as reinforcements. Compos Part A-Appl S 2010; 41: 1329-1335.
28. Summerscales J, Dissanayake N, Virk A, Hall W. A review of bast fibres and their composites. Part 2-Composites, Compos Part A-Appl S 2010; 41: 1336-1344.
29. Summerscales J, Virk A, Hall W. A review of bast fibres and their composites. Part 3-Modelling. Compos Part A-Appl S 2013; 44: 132-139.
30. Codispoti R, Oliveira DV, Olivito RS, Lourenço PB, Fangueiro R. Mechanical performance of natural-fiber reinforced Composites for the strengthening of masonry. Compos Part B-Eng 2015; 77: 74-83.
31. Gobi Kannan T, Mou Wu C, Bing Cheng K. Effect of different knitted structure on the mechanical properties and damage behavior of Flax/PLA (Poly Lactic acid) double covered uncommingled yarn composites. Compos Part B-Eng 2012; 43: 2836-2842.
32. BS ISO 3341:2000, Textile glass-Yarns-Determination of breaking force and breaking elongation.
33. BS EN ISO 527-1:2012, Plastics. Determination of tensile properties. General principles.
34. BS ISO 3342:2011, Textile glass-Mats- Determination of tensile breaking force.
35. O'Donnell A, Dweib MA, Wool RP. Natural fiber composites with plant-oil based resin. Compos Sci Technol 2004; 64:1135-1145.
36. BS EN ISO 527-4:1997, Plastics. Determination of tensile properties. Test conditions for isotropic and orthotropic fibre-reinforced plastic composites.
37. Moothoo J, Allaoui S, Ouagne P, Soulat D. A study of the tensile behaviour of flax tows and their potential for composite processing. Mater Design 2014; 55:764-772.
38. Moore DS. Tests of Chi-Squared Type. In: D'Agostino RB, Stephens MA, editors. Goodness-of-fit Techniques. New-York: Marcel Dekker, 1986. p.63-95, 526.

39. Van de Weyenberg I, Ivens J, De Coster A, Kino B, Baetens E, Verpoest I. Influence of processing and chemical treatment of flax fibres on their composites. Compos Sci Technol 2003; 63: 1241-1246.
40. http://www.gurit.com. [Online] [Cited: 20 april 2012.]
41. BS EN ISO 12215-5:2008 + A1:2014, Small craft-Hull construction and scantlings-Part 5: Design pressures for monohulls, design stresses, scantlings determination.
42. Shah DU, Schubel PJ, Licence P, Clifford MJ. Determining the minimum, critical and maximum fibre content for twisted yarn reinforced plant fibre composites. Compos Sci Technol 2012; 72: 1909-1917.
43. Sriramula S, Chryssanthopoulos MK. Quantification of uncertainty modelling in stochastic analysis of FRP composites, Compos Part A-Appl S 2009; 40: 1673-1684.
44. ASTM D 7264/D7264 M -07; Standard test Method for flexural properties of Polymer Matrix composite Materials.
45. Ramli J, Hadi AS, Jeefferie AR, Mahat MM. A preliminary Study on the effects of Photoinitiator and UV Curing Exposure Time to the Mechanical and Physical Properties of the Epoxy and Vinyl Ester Fiber Glass Laminated Composites. Int J Eng Technol 2010; 10: 14-21.
46. Appendix: Mechanical Properties of Composite Materials' Constituents. In: Shenoi RA, Wellicome JF, editors. Composite Materials in Maritime Structures Volume 2 Practical Considerations. Cambridge: Cambridge University Press, 2008. p. 300.

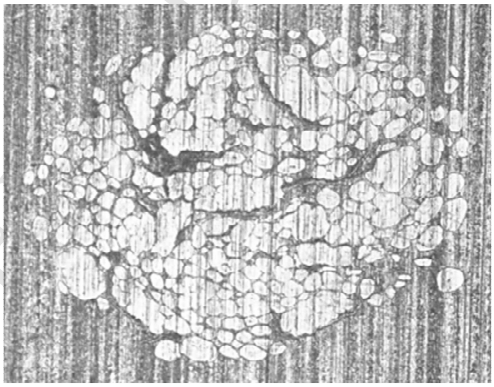

Figure 1: Cross-Sectional area of a flax yarn (observed at a magnification of 20)

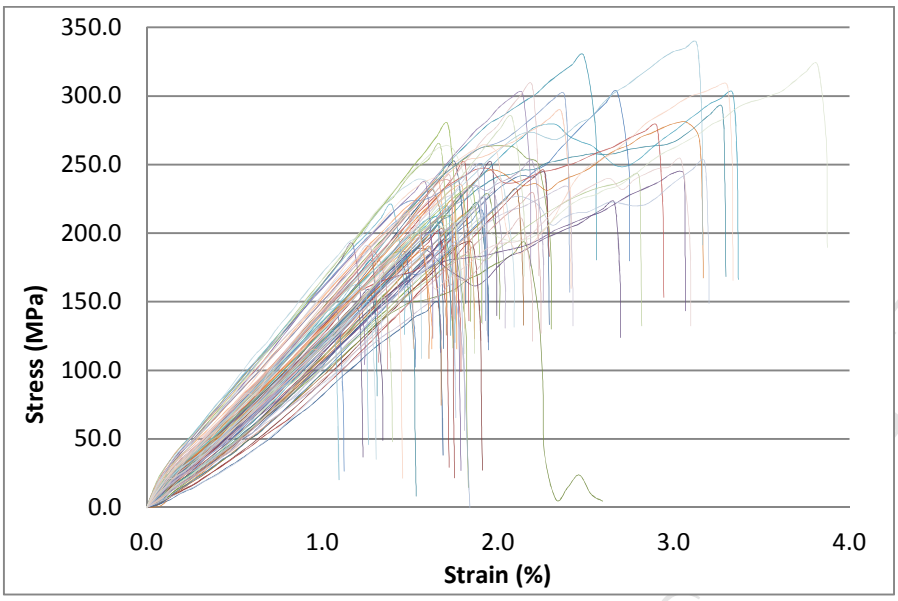

Figure 2: Stress-strain curves for 95 flax yarns of 500 mm gauge length under tension.

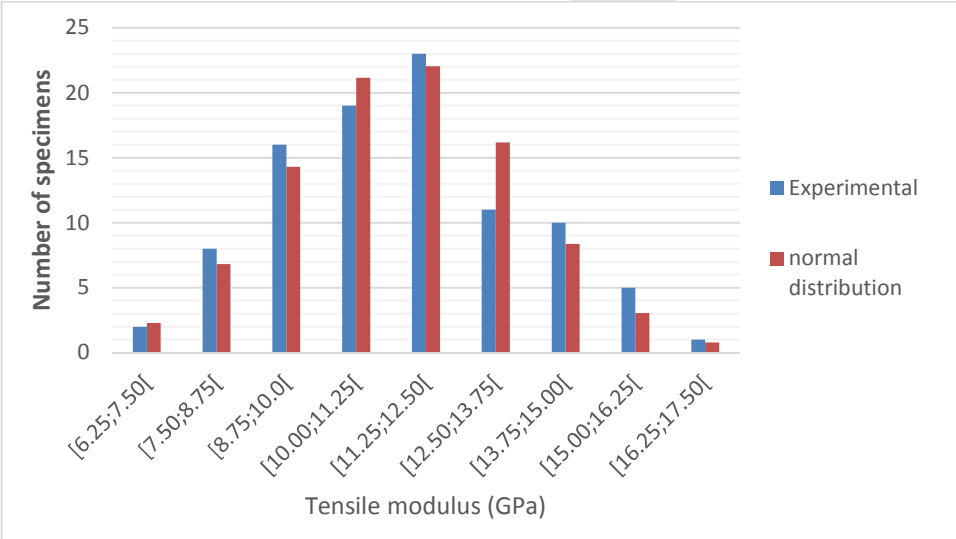

Figure 3: Statistical distribution of the Young's modulus for 95 yarns

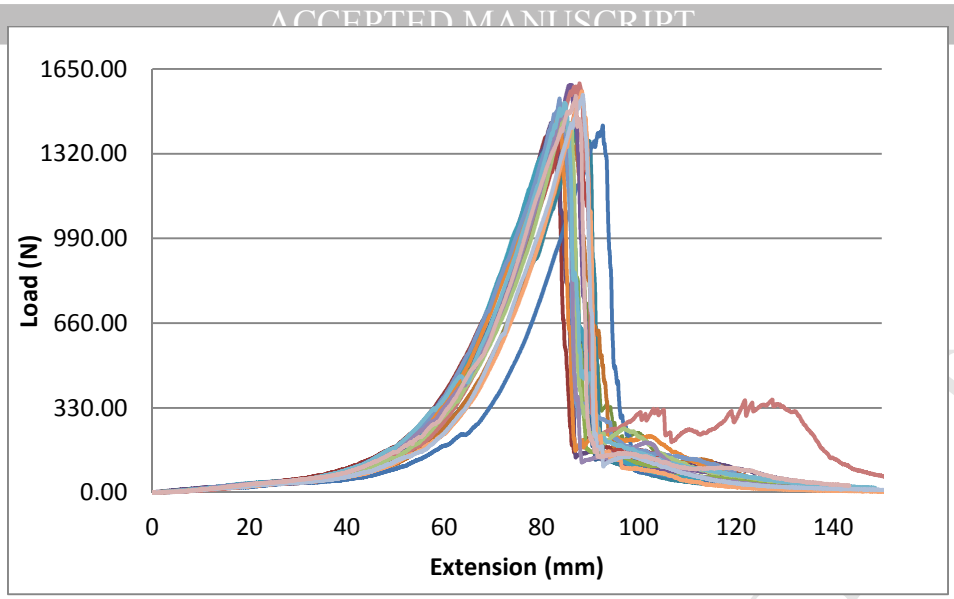

Figure 4: Load-Extension curves for 20 cloth specimens tested in tension

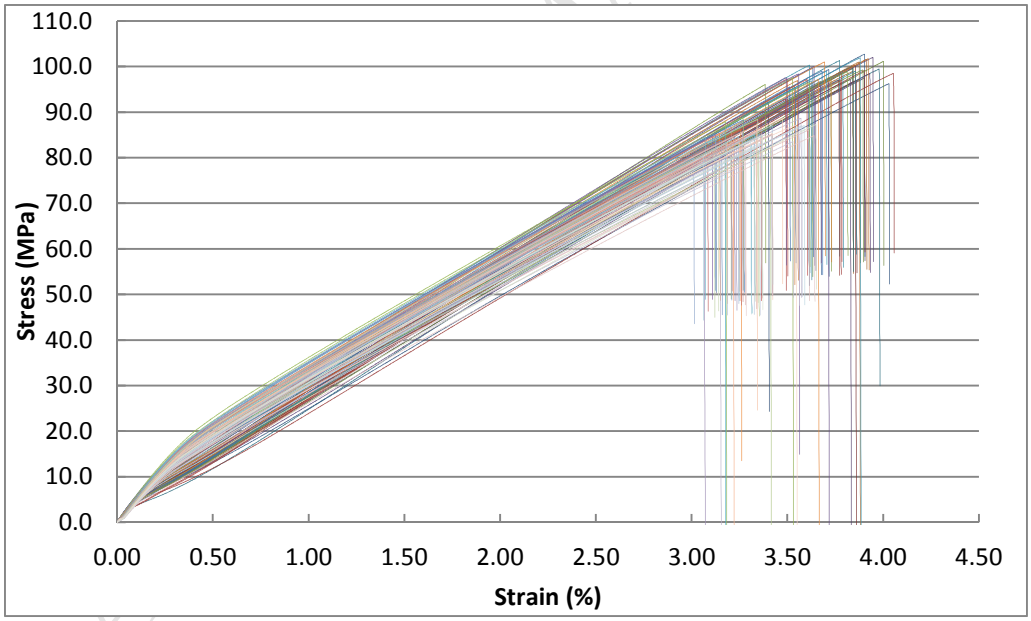

Figure 5: Stress-strain curve for 95 composite specimens tested in tension

Table 1: Description of the cloth, "FlaxPly" from the manufacturer

Fibre areal density (g/m^2)	222.1
Yarn linear density (Tex)	104.2
Weave style	Twill (2/2)
Yarns /cm (warp direction)	10.2
Yarns/cm (weft direction)	10.1

Table 2: Statistical results of the yarn linear density

	Mass (g) of 1cm yarns (100 specimens)	Yarn fineness (tex) (length: 1cm)	Yarn fineness (tex) (length: 600 mm) (121 specimens)
Mean	0.00143	143	132
STDEV	0.00035	35.2	16.7
CoV (%)	24.6	24.6	12.6
Min	0.00067	67	92.8
Max	0.00232	232	173

Table 3: Statistical analysis of yarn cross sectional area (mm^2)

	Freehand tool	Ellipse formula	Circle formula		
			Minor diameter	Major diameter	Mean diameter
Mean	0.101	0.090	0.080	0.115	0.097
STDEV	0.024	0.024	0.025	0.037	0.028
CoV (%)	24.1	26.7	31.2	31.9	28.9
Min	0.052	0.043	0.038	0.052	0.046
Max	0.159	0.146	0.153	0.228	0.168

Table 4: Yarn tensile test data based on 95 specimens

	Gauge Length (mm)	Breaking Force (N)	Tensile Breaking Stress (MPa)	Breaking Strength (N/tex)	Tensile Modulus (GPa)
Mean	501	22.6	224	0.17	11.4
STDEV	1.83	4.59	45.5	0.03	2.11
CoV (%)	0.37	20.3	20.3	16.0	18.6
Min	497	11.6	115	0.10	6.38
Max	508	34.1	339	0.23	16.7

Table 5: Statistical results of the flax cloth aerial density based on 100 specimens

	Cloth aerial density (g/m^2)
Mean	283
STDEV	23.9
CoV (%)	8.43
Min	233
Max	342

Table 6: Statistical results of the cloth tensile breaking force based on 20 specimens

	Tensile breaking force (N)
Mean	1491
STDEV	62.4
CoV (%)	4.0
Min	1348
Max	1594

Table 7: Statistical values of the fibre weight and volume fractions of an 8 layer flax/epoxy laminate

	Breadth (mm)	Length (mm)	Thickness (mm)	v_c (mm^3)	W_f (%)	W_m (%)	ρ_c (kg/m^3)	V_f (%)
Mean	25.32	249.8	4.31	27 300	44.1	55.9	1220	37.2
STDEV	0.467	1.21	0.19	1 700	1.88	1.88	6.44	1.8
CoV (%)	1.84	0.49	4.37	6.23	4.27	3.377	0.53	4.8
Min	24.19	247.0	4.03	24 740	41.0	51.3	1210	34.3
Max	26.14	253.3	4.65	30 210	48.7	59.1	1240	41.6

Table 8: Statistical tensile properties of an 8 layer flax/epoxy laminate

	Breaking strength (MPa)	Breaking Strain (%)	Young's modulus (GPa)
Mean	90.9	3.50	8.18
STDEV	7.18	0.27	0.42
CoV (%)	7.89	7.76	5.08
Min	78.9	3.01	7.45
Max	103	4.05	9.31