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Digital image correlation as a strain measurement technique for fibre tensile tests

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ABSTRACT

A method is presented to test fibres in tension using direct strain measurement. This eliminates the need to test the fibres at multiple gauge lengths to correct for machine compliance, reducing the number of samples. Additionally, fibre slippage can contribute to the underestimation of the stiffness since this is not considered in the correction procedure. Steel fibres with a diameter of 30 μm, and a known stiffness of 193 GPa, were tested in tension using indirect methods and the direct strain method. Direct strain measurement resulted in a stiffness of 187 ± 12 GPa while the lowest and highest stiffness obtained by the indirect methods are 140 ± 2 GPa and 150 ± 4 GPa. The underestimation by the indirect measurement strain methods show the need for a new method. To demonstrate the applicability of the new test method to natural fibres, the properties of *technical* flax and bamboo fibres were determined.

1. Introduction

Fibre tensile tests are a way to determine the fibre's mechanical properties. It is the preferred method when limited material is available, in material development stage. The fibre's tensile properties are needed to perform micromechanical analyses and mechanical modelling of these materials and their composites. For synthetic fibres, the fibre properties are often provided by the manufacturers. However, when testing new materials, and especially from natural resources, datasheets are often not available.

Natural fibres are becoming increasingly important as a reinforcing fibre in composite materials. Therefore, the need for consistent fibre properties increases. Additionally, fibre manufacturers, or cultivators in the case of natural fibres, should be able to rely on fibre properties to measure the quality of the produced material. Unfortunately, the literature reveals a large range of the measured natural fibre properties, as can be seen in Table 1. A part of this variation can be attributed to the inherent variability in plant materials, but this is unlikely to be a complete explanation. There is a need for a consistent fibre testing method where the scatter is only a function of the material variability and not of the testing setup. Summerscales et al. [1] provide a checklist for the material related data and testing conditions that always should be reported in order to compare the experimental data with literature.

There are a few problems when testing natural fibres, that can lead to a wide range of results [2,3]. Firstly, the literature does not always clearly state whether tests are performed on an *elementary* fibre (a single plant cell) or a *technical* fibre (a bundle of *elementary* fibres). It is well recognised that *elementary* fibres have higher stiffness and strength compared to *technical* fibres [4]. Secondly, when testing *technical* fibres at very short gauge lengths, *elementary* fibres can get gripped from end to end. The short gauge length reduces the probability of finding a weak location and reduces the effects of the weak inter-*elementary* fibre middle lamellae [3]. Besides the problems mentioned above, some other test related influencing factors are known: the strain rate (viscoelastic behaviour of the fibres), the environmental conditions (hygroscopic behaviour of natural fibres) and the gripping method (gripping of frame or fibre) should therefore always be reported [5,6].

Haag et al. [2] summed up the previous issues, and added the importance of the determination of the cross sectional area. Via different optical techniques such as flatbed scanner, light microscopy and laser based analysis they determined, from the projected diameter, the cross-section of the fibre. Furthermore, the authors tried different calculations to determine the cross-sectional area, assuming either a circular or an elliptical shape. It was seen that the scatter induced by the different calculation methods, resulted

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Table 1
Mechanical properties of flax and bamboo technical fibres.

Young's modulus (GPa)	Strength (MPa)	Failure strain (%)	Comment	Ref.
Flax				
31 ± 12	305 ± 120	1.3 ± 0.4	Gauge 75 mm, 1 mm/min, green flax	[4]
32 ± 12	310 ± 120	1.1 ± 0.4	Gauge 75 mm, 1 mm/min, retted flax	[4]
Bamboo				
33.37	639 ± 175–813 ± 94[a]	2.0 ± 0.6–2.9 ± 0.7[a]	Gauge 5, 15, 25, 35, 1 mm/min, steam explosion	[9]
43	775 ± 103–860 ± 119[a]	1.7 ± 0.2–1.9 ± 0.3[a]	Gauge 5, 10, 25, 40, 1 mm/min, mechanical extraction	[16]
35.91	503	1.4	Mechanical extraction	[20]
19.67	341	1.73	Chemical extraction	[20]
35.9 ± 13.1	441 ± 220	1.3	1 mm/min, steam explosion	[21]

[a] Weakest test length – strongest test length.

in a large variation which is partly responsible for the high scatter on the natural fibre properties. Thomason et al. [7] embedded *technical* flax and sisal fibres after tensile testing, and traced the contour of the fibre to determine the cross sectional are. This method revealed a large difference between 'projected diameter techniques' and true diameter determination. In this research a gravimetric method was used, for the determination of fibre diameter, as is outlined in Defoirdt et al. [9]. It is believed that this method to determine the cross-section is user independent and can lead to a reduced spread on the fibre properties of natural fibres, avoiding the struggle of assuming a cross-sectional geometry of the irregular fibre and avoiding numerous measurements for each fibre.

A final influencing factor, which is normally not addressed, is the importance of a correct strain measurement method, and this is investigated in this paper. The strain in a fibre tensile test is often measured indirectly via the grip displacement, due to the difficulties in measuring it in a direct manner. To compensate for the system compliance, ASTM C1557-14 [8] prescribes a procedure to perform the data reduction. Defoirdt et al. [9] have developed an alternative procedure to correct the strain values to calculate the fibre properties. However, for both methods it is necessary to test at least at 3 different gauge lengths. Hence, the method requires a significant number of fibres. It remains to investigate whether the correction on the strain for system compliance covers all the effects occurring during a tensile test. Fuentes et al. [10] developed a technique to measure local *technical* fibre properties by applying a speckle pattern on the fibre itself. The analysed length hereby is a few millimetres, therefore giving insight in the local behaviour of the fibre. With the strain mapping it was also possible to indicate movements of *elementary* fibres.

In this research, a novel method is presented for direct measurement of strain during single fibre tensile testing. The new technique is compared to the existing methods, including the different ways of data reduction for tensile fibre tests. Cold drawn steel, a material with known properties, is used to assess the accuracy of each method. Finally, two types of natural fibres, bamboo and flax are characterised by the new technique.

2. Materials & methods

2.1. Steel fibres

Cold drawn stainless steel (type 316L) fibres with a Young's modulus of 193 GPa and a diameter of 30 μm were supplied by NV Bekaert SA. The continuous steel fibres are produced in a bundle drawing process in which steel wires are embedded in a copper matrix and subsequently cold drawn to reduce the bundle diameter. After this process the copper matrix is removed. The cross-sectional area of the fibres after drawing has a constant value but has a polygonal appearance [11]. Optical microscopy showed that the fibre diameter did not vary along the fibre length. The average cross sectional area of the fibre (A) was calculated by Eq. (1).

$$A = \frac{m}{\rho l} \quad (1)$$

In the above equation m is the fibre mass, ρ is the fibre density and l is the fibre length. The fibre mass was determined with an analytical balance (Mettler AT 261 DeltaRange, Mettler Toledo) accurate to 10^{-5} g. The density of the steel fibres was 8.00 g/cm^3.

2.2. Flax

Technical flax fibres (*Linum usitatissimum L.*) were sampled from FlaxTape 200, a unidirectional flax fibre tape for composite applications with an areal density of 200 g/m^2, supplied by Lineo NV. The tape consists out of scutched and aligned *technical* fibres, originating from different harvests to average out variations in the fibre properties. The density of the fibres was determined using a gas pycnometer, Beckman model 930, in which helium gas at a pressure of 0.5 bar was used as the displacement medium. Prior to the density measurement, the fibres were cut to a length of 1 cm and vacuum dried for 19 h at 60 °C. The measured density was 1.47 ± 0.01 g/cm^3. For the tensile tests, the fibres were cut to a length of 10 cm, dried for 24 h at 60 °C and subsequently conditioned at 50% relative humidity (RH) and 21 °C for at least 24 h. In the latter condition, the mass of the fibres was measured to calculate the average cross sectional area using Eq. (1).

2.3. Bamboo

Bamboo fibres (*Guadua angustifolia Kunth*) were sourced from Columbia, the Coffee Region, at 1300 meters above sea level with an annual average temperature of 23 °C and an annual average precipitation of 2200 mm and a relative humidity of 80% according to the environmental authorities of the region [12]. From the bamboo culms, which have an average culm diameter of 11 cm and a height of 20–23 meter, fibres were fully mechanically extracted from the middle part of the culm using an in house developed technique [12]. The density and average cross sectional area of the fibres was determined following the same procedure and the same specimen preparation as for the flax fibres. The measured density was 1.36 ± 0.02 g/cm^3.

2.4. Fibre tensile test set-up

To compare the different existing methods, steel fibres with known Young's modulus were chosen to experimentally determine the fibre modulus. The fibre was glued onto abrasive paper (PS11A grain 1000, Klingspor) frame using a double-sided glue roller (Permanent Pritt glue roller, Henkel). Although, this method of gripping may lead to premature failure of the fibre due to damage,