SINGLE FIBRE TENSILE TESTING: ANALYSING THE INFLUENCE OF FIBRE MISALIGNMENT TO QUANTIFY UNCERTAINTIES IN PROPERTIES IDENTIFICATION

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Keywords: fibre, tensile testing, Young's modulus, stress at failure, analytical modelling and finite element simulation

Abstract
During a tensile test on a single fibre, improper positioning of the fibre or of the paper frame in the tensile machine can lead to a misalignment between the fibre and the tensile axis which induces errors or uncertainties in the determination of mechanical properties. Thus, this work proposes to quantify the error on Young's modulus and on the stress at failure assessments as a function of the misalignment angle. Assuming the fibre is isotropic, a finite element simulation and an analytical model based on beam theory were developed. As expected, Young's modulus and strength are systematically underestimated as the angle between the tensile axis and the fibre increases. For instance, a 10° angle results in 4.49% decrease in Young’s modulus and 1.52% decrease in stress at failure. It is now possible to assess and evaluate the error made on these mechanical properties and to take it into account when analysing experimental results or developing tensile test machines. This work constitutes a first step towards a more sophisticated 3D finite element model, with the aim to assess the impact of misalignment on fibres with more complex geometries and material behaviour, including anisotropy.

1. Introduction

Accurately determining the longitudinal properties of single plant fibres is essential for predicting the mechanical performances of composite materials integrating them. Among the various characterisation methods, tensile testing remains the most widely used for identifying fibres’ longitudinal properties, in particular Young's modulus, stress and strain at failure.

However, this method encounters specific challenges due to the small size of the fibres. Current state-of-the-art research has addressed the quantification of various sources of epistemic uncertainty inherent in this test through analytical methods and finite element simulations [1]. It is still important to reduce them in order to better describe the stochastic uncertainties of the different types of fibre.

Among others, preparation and handling of the fibre prior to testing can cause damage. Measuring accurately the gauge length of the fibre and, in the case of plant fibres, their cross-sectional area is challenging. Tensile testing on single fibre involves small forces and displacements, making the position of the force and displacement sensors relative to the fibre crucial [2]. Determining test device compliance and strain also introduces additional uncertainties [3].

Moreover, during testing, the manual positioning and alignment of the fibre on the fibre holder, paper frame, may induce a misalignment between the fibre and the tensile axis. However, the analysis and quantification of the impact of this angle on the determination of the Young's modulus have received limited attention [4, 5]. To the best of the authors' knowledge, the influence of this angle on the stress at failure remains largely unexplored [1].

The aim of this study, based on an analytical model and a finite element simulation, focusing on an isotropic fibre with a circular cross-section, represents a first step towards quantifying the influence of this angle on the identified mechanical properties. This is a necessary prerequisite for understanding more complex material behaviours (anisotropy, viscoelasticity,…) of the fibre or more intricate geometries of its cross-section.

2. Materials and methods

2.1. Analytical model

To evaluate the influence of an angle between the fibre and the tensile axis on the measurement of the Young's modulus and the stress at failure, an analytical model using the Euler-Bernoulli beam theory is developed. A single fibre, free from defects, with Young's modulus E, stress at failure σ_f, initial length L and circular cross-section of diameter D is positioned in a tensile testing device (Figure 1). $(O,\vec{x},\vec{y},\vec{z})$ is the global coordinate system while $\left(O,\vec{n},\vec{s}=\vec{y},\vec{t}\right)$ is the coordinate system linked to the fibre. A point has coordinates $(n,0,t)$ in the fibre coordinate system. The ends of the fibre are clamped at point A and at the centre of the fixed lower jaw, point O. A tensile force $\vec{F}$ along $+\vec{z}$ is applied to the upper, movable jaw at A which causes the displacement u_z along the $\vec{z}$ axis. A roller support allows the translation of this jaw parallel to the axis $\vec{z}$ during the application of $\vec{F}$. The fibre is initially positioned at an angle θ with respect to the tensile axis. As this angle varies little during the tensile test, the angle is assumed to be constant. The rotation of the fibre around $\vec{y}$ is blocked at points O and A.

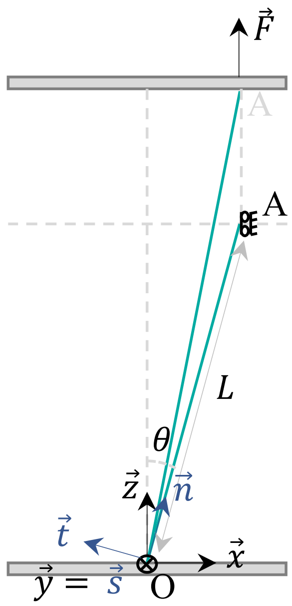

Figure 1. Single fibre tensile test with an angle θ between the fibre and the tensile axis

The Young's modulus in the $\vec{z}$ direction is E_{mes}. It is determined by the ratio between stress and strain calculated in the global coordinate system according to equation (1), with the tensile force F, the circular cross-sectional area of the fibre and the displacement u_z which can be measured experimentally. The relative deviation between E_{mes} and E is defined by relation (2).

σ_{mes} is the value of the stress at failure in the $\vec{z}$ direction. It is determined by the ratio between the force F, at which the stress in the longitudinal direction of the fibre, σ_{nn}, reaches the stress at failure, and the circular cross-sectional area of the fibre. It is observed that the bending stress is negligible relative to tensile stress. In this work, the stress at failure is determined at the middle of the fibre ($n=\frac{L}{2}$ in equation (3)), which dissociates the effect of the angle on the stress at failure from that of the stress concentration at the clamping point. σ_{mes} is obtained when the stress in the longitudinal direction of the fibre at its middle reaches the stress at failure. Relation (4) then gives the relative deviation between σ_{mes} and σ_f.

$$F\frac{4}{\pi D^2}=E_{mes}\frac{u_z(L)}{L\cos(\theta)} \quad (1)$$

$$\Delta E\ (\%)=\frac{E_{mes}\text{-}E}{E}=\left(\cos^3(\theta)+\frac{3D^2}{4L^2}\cos(\theta)\sin^2(\theta)\text{ -1}\right)100 \quad (2)$$

$$\sigma_{mes}(n,t)=\frac{\cos^2(\theta)+\frac{3}{4}\left(\frac{D}{L}\right)^2\sin^2(\theta)}{\cos(\theta)+12\sin(\theta)\left(n-\frac{L}{2}\right)\frac{t}{L^2}}\sigma_f \quad (3)$$

$$\Delta\sigma(\%)=\frac{\sigma_{mes}\text{-}\sigma_f}{\sigma_f}=\left(\frac{\cos^2(\theta)+\frac{3}{4}\left(\frac{D}{L}\right)^2\sin^2(\theta)}{\cos(\theta)}\text{-1}\right)100 \quad (4)$$

2.2. Finite element modelling

In addition to the analytical model, a simulation of the tensile test is performed with various values of the angle θ between the fibre and the tensile axis. A single fibre tensile test is simulated with finite element analysis using COMSOL Multiphysics® software.

As this simulation is a first step towards modelling complex geometries of fibre cross-sections, notably of plant fibres, a 3D model is necessary to account for the presence of the angle θ between the fibre and the tensile axis.

The fibre is assumed to be a right circular cylinder with diameter 14.4 μm made of homogeneous, isotropic, defect-free glass with Young's modulus, E, equal to 77 GPa. θ is the angle between the tensile axis and the fibre axis. In order to keep a constant initial gauge length in the $\vec{z}$ direction (1 mm) in all cases, the initial fibre length, L, is adapted at each angle ($L=\frac{1}{\cos\theta}$ mm). Both sections at the ends of the fibre are perpendicular to the tensile axis and are consequently elliptic.

To simulate the tensile test, all the nodes of the section at the lower end of the fibre are completely blocked ($\{u\}=0$) while all the nodes of the section at the upper end are gradually moved only along the $\vec{z}$ direction until a final displacement of $50\ \mu m$ $\left(u_x=0, u_y=0, u_z=50\ \mu m\right)$ (Figure 2). The displacement increment is $5\cdot 10^{-3}\ \mu m$ because it is necessary to detect precisely when the stress in the longitudinal direction of the fibre, σ_{nn}, reaches the given stress at failure σ_f.

When it comes to meshing, as both ends of the fibre endure stress concentration, these ends and the areas close to them are more finely meshed than the middle of fibre (Figure 2). The whole fibre is divided into 238 640 elements, mainly triangular prisms.

The stress at failure for each value of θ is determined at the cross-section in the middle of the fibre to separate the effect of the angle on the stress at failure from the stress concentration at the clamping point. When the stress in the longitudinal direction of the fibre, σ_{nn}, at a point on the plane, perpendicular to the tensile axis in the middle of the fibre, reaches the glass fibre stress at failure σ_f of 3.3 GPa, the value of the displacement is then recorded. As for the analytical beam model, the bending stress, σ_{nt}, is at most $2.5\cdot 10^{-4}$ smaller than the tensile stress σ_{nn} in the local coordinate system. To this displacement corresponds a stress σ_{zz}, which integrated on this elliptic surface, gives the force F_z. The stress at failure, σ_{sim}, is the quotient of F_z by the circular cross-sectional area of the fibre because experimentally, the existence of such an angle is not necessarily known. The relative deviation between σ_{sim} and σ_f is $\Delta\sigma = \frac{\sigma_{sim}-\sigma_f}{\sigma_f}100$.

The Young's modulus for each value of θ, E_{sim}, is determined from the stress, quotient of F_z by the circular cross-sectional area of the fibre, and the strain, quotient of the imposed displacement u_z by the initial gauge length. The relative deviation between E_{sim} and E is $\Delta E = \frac{E_{sim}-E}{E}100$.

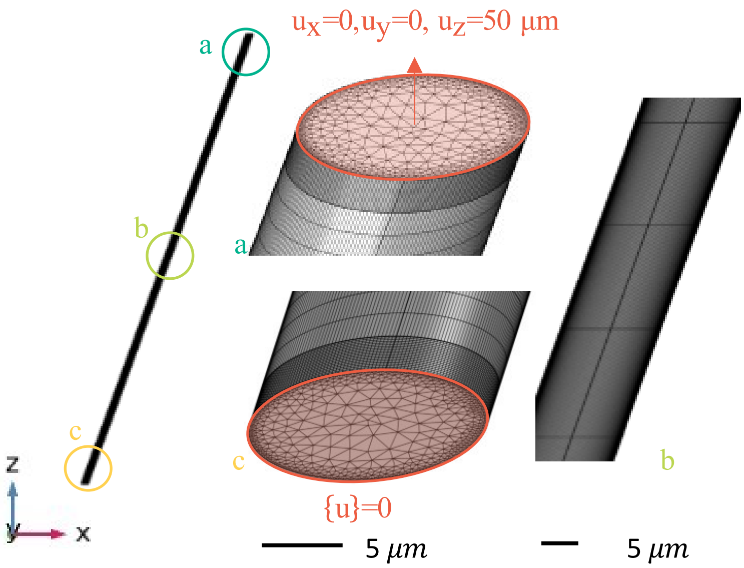

Figure 2. Boundary conditions and mesh at a) the top end, b) the middle and c) the bottom end of the fibre of tensile test finite element model

3. Results and discussion

In Figure 3, the relative deviations ΔE and Δσ, worked out from the analytical model and the finite element simulation, are plotted as functions of the angle θ. As expected, the results of the analytical model and those of the finite element simulation are the same, for a fibre of the same length L and the same cross-sectional diameter D.

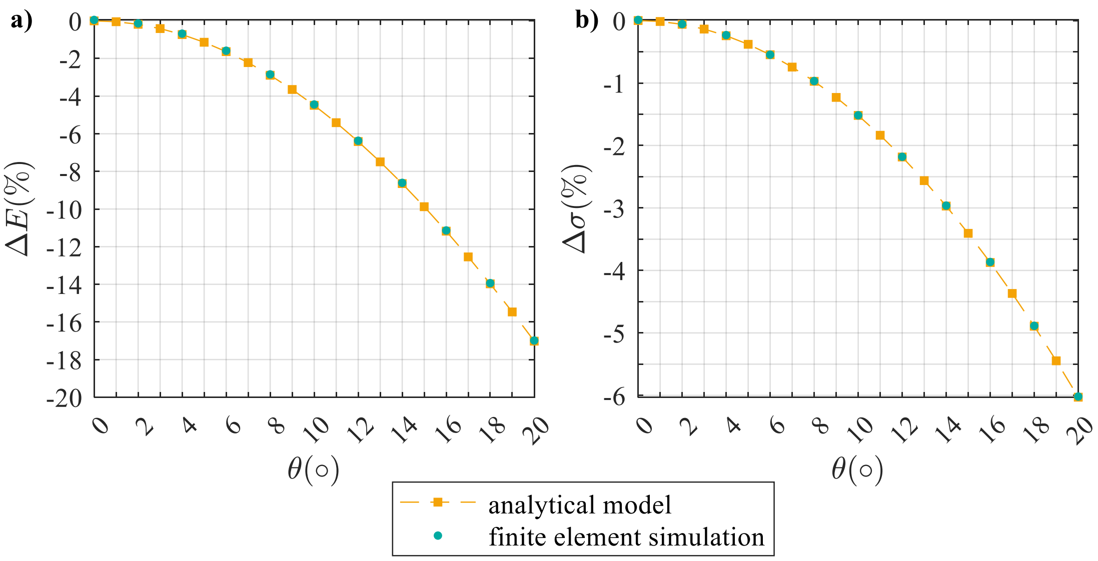

Figure 3. Evolution of the relative deviations ΔE (a) and Δσ (b) as functions of θ, by the analytical model and by the finite element simulation

For ΔE, the points plotted by the finite element simulation are on the curve given by the analytical model. ΔE is a decreasing function of the angle θ. Furthermore, it varies as a cubic function of cosinus θ as the quotient $\frac{D}{L}$ is negligible. The Young's modulus is therefore underestimated as θ increases. For instance, when θ equals $10°$, ΔE is equal to -4.49 %.
Regarding Δσ, the analytical model curve goes through the points of the finite element simulation. Δσ is also a decreasing function of the angle θ. The stress at failure is thus underestimated as θ increases. As $\frac{D}{L}$ becomes insignificant, Δσ varies primarily as a function of cosinus θ. For the same angle θ, the underestimation of the stress at failure is less significant than for the Young's modulus. For instance, when θ equals $10°$, Δσ is equal to -1.52 %.

This work makes it possible to estimate a maximum angle for which the error in identifying the Young's modulus becomes significant. Further work could be considered, in the design of a testing device for measuring or limiting the misalignment, in order to minimise the error on the identified mechanical properties. The use of the finite element model with more complex cross-section morphologies should make it possible to study the additional error and its potential impact on the design of the testing device.

4. Conclusion

The existence of an angle between the fibre and the tensile axis leads to a systematic underestimation of the Young's modulus and the stress at failure.

A good agreement between the analytical model and the finite element simulation is observed. This analytical model can be used in simple cases because the assumptions of the beam model have no impacts on the result. In fact, the misalignment error is evaluated in the middle of the fibre, without taking into account the stress concentration at the clamping points.
A 3D finite element model could subsequently be used for more complex fibre geometries and material behaviours for which the development of an analytical model would be more difficult. It would also allow us to see the influence of misalignment on the increase in stress concentration at the jaws tips.

Acknowledgments

This work is supported by the Région Bourgogne Franche-Comté. This work has also been achieved in the frame of the EIPHI Graduate school (contract "ANR-17-EURE-0002").

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