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A new method for the measurement of static and dynamic Young's moduli of long fibres

Tomasz Więcek *

Department of Physics, Faculty of Mathematics and Applied Physics, Rzeszów University of Technology, Powstańców Warszawy Street 12, 35-959 Rzeszów, Poland

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ABSTRACT

This article describes a new laser systems to measure the Young's modulus of a long fibre based on the diffraction of light. Two setups are presented. The first setup has been used to measure the static Young's modulus of a thin basalt fibre (10 μm diameter, 93 mm length). The second setup called "impulse mechanical spectrometer" was used to measure the dynamic Young's modulus of a long polyamide fibre (128 μm diameter, 371 mm length). A change of the vibration frequency is achieved by changing the length of the fibre or the load. The damping coefficient was also estimated in the dynamic characterisation. The presented experimental method does not require calibration.

1. Introduction

Polymer composites containing long fibres in a polymer matrix are now widely used as engineering materials. Usually the composite's constituents such as the fibres and the epoxy resin have different physical properties. Mechanical components made from composites are often subjected to static and dynamic loading. Therefore, knowledge of the mechanical properties of the fibres and of the polymer matrix is important. Particularly, knowledge of the static and dynamic Young's moduli of the fibre is required to optimise the design of composites. Recently new fibres called "high performance fibres" [1] have been developed. There is need to determine their heat conductivity, breakdown strength, shear modulus and fundamental mechanical properties [2].

The mechanical properties of fibres generally depend on their geometry. The properties of thin fibres may depend strongly on the properties of the bulk material and they often exhibit a dependence on the thickness [2,3] as well as on the length of the fibre [4]. Additionally, the state of the surface of the fibre [5], the fibre history [6] and the manufacturing process [7] are known to determine the measurable properties. For these reasons, there is need for a wide variety of techniques for a complete mechanical characterisation of fibres.

The standard instruments used for the determination of mechanical properties are unsuitable for the investigation of thin fibres. An universal testing machine cannot be used for precise studies of Young's moduli of thin fibres with diameter in the order of 10 μm because of restrictions on the sample geometry [2,6,8]. Viscoelasticity is also studied by using an ultrasonic instrument [9], an impulse mechanical spectrometer (IMS) [10], or by dynamic mechanical analysis (DMA). In all cases, an oscillatory force (stress) is applied to the sample and the resulting displacement (strain) is measured [11]. Due to difficulties with sample fixing and force sensitivity, none of the techniques mentioned above can be used for reliable measurements of thin fibres [12,8]. For fibres that cannot be handled using direct techniques, optical methods have been proposed. Known general-purpose techniques utilise contactless speckle interferometry [8] and geometric shadow [6]. Specialized methods are applicable to optical fibres [13,14] and suitable for the micro-characterisation of fibres in a composite [15].

In this contribution another approach is presented. The method is based on a non-contact measurement of the length by diffraction of visible light. This type of measurement allows for a reduced load on the fibre investigated. The use of diffraction permits an exceptionally precise measurement of the displacement without the need for calibration. The laser technique presented here is highly sensitive, non-inertial and is a non-contact technique [16]. Therefore the deformation of the sample can be measured to within a few micrometres allowing to measure thinner fibres with applied forces well in the elastic range.

The proposed method has advantages over the previous methods. Compared to speckle interferometry [8], it allows for both static and dynamic measurements. There is no need for coating reflective fibres. Compared to the method of Perrin et al. [6], longitudinal rather than transversal vibration is being observed.

* Tel.: +48 178651744.
E-mail address: ftkwiece@prz.edu.pl

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The fibre is fixed at both ends. There is no need to choose the length and the thickness such that the lateral vibration of the free end is being observed. On the contrary, the technique presented here imposes no limit on the length of the fibre being tested. This allows for measuring very small strain. The effect of nonuniform strain in the grip area [8] can be made arbitrarily small by using long fibres. Unlike in Ref. [6], the amplitude of the longitudinal vibration occurring after the pulse excitation is observed directly.

Two versions of the experimental setup are being presented. One version is designed for the measurement of the static Young's modulus, which is estimated directly from the elongation of the fibre. The other version is suitable for the measurement of the dynamic Young's modulus. The impulse force initiates longitudinal resonant vibration of the fibre. The time-dependent elongation of the fibre is measured optically. Then, it is fitted to the general relaxation formula from which the dynamic Young's modulus and the damping coefficient are estimated.

Static measurements are performed on a basalt fibre of length 93.1 mm and diameter 10.1 μm. Dynamic measurements are performed on a polyamide fibre of length 371 mm and diameter 128 μm. The samples are selected to demonstrate the feasibility of measuring fibres of diameter as small as 10 μm and of arbitrary length.

Fibres that must be measured with very small load have been selected. Basalt fibre has standard value of Young's modulus of 89 GPa [17,18]. The breaking strain for basalt is at 2%. Polyamide (nylon) has complex viscoelastic properties, which have been also studied in detail for fibres [19]. The static Young's modulus of polyamide fibres is in the range of 2–5 GPa [19–22]. The breaking strain of a polyamide fibre is at 20–30% [23,24]. However, linear elastic region is limited an elongation of 1% [19].

The paper is organised as follows. In Section 2, the basic theoretical concepts concerning elastic properties and far-field light diffraction are briefly reviewed. In Section 3, the experimental setups for the investigation of static and dynamic elastic properties are explained in detail. In the same Section, the methodology of the data analysis is explained. Finally, in Section 4, measurement results obtained for fibres are being presented.

2. Theory

2.1. Static and dynamic Young's moduli

The static and dynamic Young's moduli are fundamental for the characterisation of elastic materials. The static Young's modulus E_S is defined as the ratio of uniaxial stress to uniaxial strain in the range of stress for which Hooke's law holds [25]. The static Young's modulus E_S can be calculated by dividing the tensile stress by the tensile strain for the elastic (linear) part of the stress–strain curve:

$$E_S = \frac{\sigma}{\varepsilon} = \frac{F/S}{\Delta L/L_0}, \tag{1}$$

where F denotes the force exerted on a sample under tension, S the cross-section area through which the force is acting, ΔL the amount by which the length of the object changes, L_0 the original length of the object, σ the stress and ε the relative strain.

The dynamic Young's modulus (E_D) is the ratio of stress to strain under oscillatory load. In purely elastic materials the stress and strain occur in phase, so that the response of one occurs simultaneously with the other. In purely viscous materials there is a phase difference between stress and strain, such that the strain lags behind the stress by $\pi/2$ radians. The behaviour of viscoelastic materials lies between purely viscous and purely elastic materials, exhibiting a phase shift of the strain in the range of 0 to $\pi/2$ (Fig. 1).

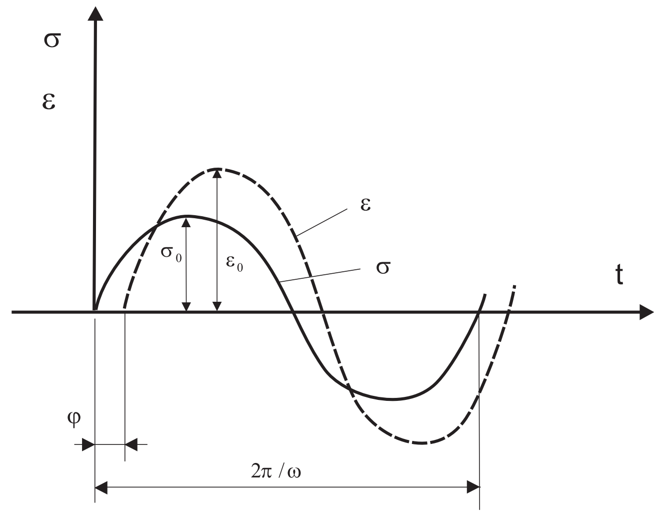

Fig. 1. Dynamic stress (σ) and strain (ε) versus time (t) in viscoelastic materials.

The dynamic stress σ and the dynamic strain ε in a viscoelastic material can be represented by the following equations:

$$\varepsilon(t) = \varepsilon_0 \sin(\omega t - \varphi), \tag{2}$$

$$\sigma(t) = \sigma_0 \sin \omega t, \tag{3}$$

where ω is the angular frequency of oscillation, t is the time variable, φ is the phase difference between stress and strain, σ_0 is the amplitude of the stress and ε_0 is the amplitude of the strain. It is assumed that the deformation is elastic and that the stress–strain relation is linear.

2.2. Fraunhofer diffraction theory

Fig. 2 presents the diffraction configuration used in this work. A laser beam passes through a slit of width d, generating a diffraction pattern on the screen at a distance Z from the slit. This pattern, consisting of a series of peaks, has its maximum intensity at the zero-order fringe located at $x = 0$, which falls off as $|x|$ increases.

The Fraunhofer theory is used to describe the diffraction of waves when the diffraction pattern is viewed at a long distance from the diffracting object [26]. In the case of diffraction on a slit, the theory gives the diffracted light intensity by the following formula:

$$I(x,d) = A^2 d^2 \frac{\sin^2\left(\frac{\pi d x}{\lambda Z}\right)}{\left(\frac{\pi d x}{\lambda Z}\right)^2}. \tag{4}$$

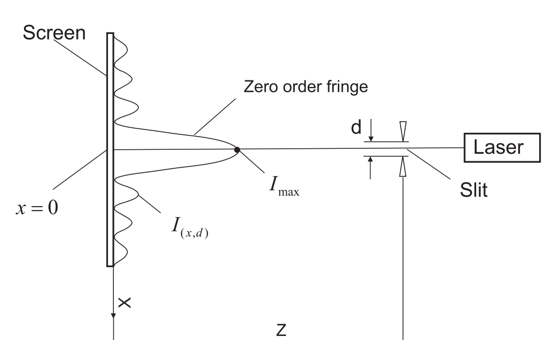

Fig. 2. The diffraction pattern produced by a single slit. I – light intensity, d – width of the slit, Z – distance between the screen and the slit.