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Viscoelastic properties of Kevlar-29 fabric tape strength member

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ABSTRACT

Kevlar®-29 strength members find wide application in tow lines, mooring lines, oil rig pendants and underwater sensor systems. In this paper, the dynamic mechanical properties of Kevlar-29 fabric tape strength member are characterized by semi-empirical means. A series of transient and harmonic tests were conducted for a typical configuration taking into account of time scales and operating conditions of practical interest. Constitutive relations based on three-parameter and five-parameter spring-dashpot discrete models were used for extracting the properties from transient tests. The parameter values obtained through transient tests were transformed to complex modulus in the frequency domain. Comparison in the frequency domain was made between the results obtained through transient tests and harmonic tests. Effects of preload and stress rates were studied. It is observed that storage modulus increases and loss factor decreases with increase in preload. At very low frequencies, analysis of the transient tests using discrete models shows lower storage modulus values compared to harmonic tests and hence does not provide reliable estimation. At higher frequencies, i.e., above 8 Hz, five-parameter discrete model based on transient tests can adequately estimate both the storage modulus and loss modulus. The transient tests indicate a rise in the loss factor at mid frequencies whereas the harmonic tests give almost flat response. Also the modulus of Kevlar fabric tape increases with increase in stress rate. Nonlinear behaviour is noticed throughout the tensile deformation response.

1. Introduction

The high strength, high modulus, low elongation, and light weight of Kevlar aramid fibres translate well into ropes and cables of many constructions, and have led to successful use of both mechanical ropes and electromechanical cables. Mechanical ropes of Kevlar-29™ with very high breaking strengths are used in tow lines, mooring lines and oil rig pendant lines. Electromechanical cables with strength members of Kevlar-29 have been successfully developed for use in underwater sensor arrays and as primary umbilicals and tether cables for unmanned undersea work vehicles for both military and commercial applications (Horn et al., 1977).

In one of the specific applications, Kevlar-29 strength member in the form of fabric tape is used in towed acoustic sensor arrays due to its ease of assembly. This tape is formed into an endless loop and runs between the end connectors of the sensor array modules. As this tape is the load-bearing member during deployment, it acts as the primary transmission path for vibrations from various sources. Since the vibrations transmitted to the acoustic sensor module induce noise in the hydrophones (Bedenbender et al., 1970; Engineer, 2001), the dynamic mechanical properties of the Kevlar fabric tape are critical factors determining the performance of the sensor system.

Kevlar-29 [Poly (*para oriented*)-phenylene terephtalamide (PPTA)] is a *p*-aramid fibre. It is a fibre with high degree of orientation and crystallinity that is spun from a liquid crystalline solution of extended chain molecules. Because of these features, Kevlar is an example of an elastic polymer fibre with a high elastic modulus, a high breaking

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stress and a low breaking strain (Wortmann and Schulz, 1995). It has a glass transition temperature above 375 °C.

Many authors have investigated the dynamic mechanical properties of Kevlar fibres (Allen and Roche, 1989; Wortmann and Schulz, 1994, 1995; Wang and Xia, 1998, 1999). Their studies have shown that, in spite of the generally assumed ‘elasticity’, Kevlar is predominantly viscoelastic owing to the noticeable contribution of the viscous component to the overall modulus. However, these studies have been conducted on fibres, and literature specifically attempting to characterize woven fabric tapes made out of Kevlar is sparse. There is a need to develop a viscoelastic model for Kevlar tape strength member that can be used in analysis tools including finite element software packages for predicting the vibration response of systems.

A three-element linear viscoelastic model was presented by Shim et al. (2001) pertaining to another similar *p*-aramid fabric, Twaron. The model presented was essentially to characterize the dynamic mechanical properties of Poly (*para oriented)*-phenylene terephtalamide [PPTA] fibres used in bulletproof fabric armour.

Sabu Sebastian et al. (2004) presented a five-parameter linear viscoelastic model for the Kevlar-29 fabric tape based on a creep study. During the above study, parametric response functions of three-parameter as well as five-parameter viscoelastic models were curve fitted on the creep test data in the time domain. It was found that the three-parameter model is inadequate to represent the dynamic behaviour of Kevlar-29 fabric tape used as a strength member. The five-parameter model was found to be in better agreement with the experimental behaviour of the tape.

The present study aims at characterizing the viscoelastic properties of the Kevlar-29 fabric tape for frequency ranges and loading conditions of practical interest. Harmonic tests and semi-empirical means based on transient tensile tests have been used in this study. Transient test data have been analysed based on three-parameter and five-parameter discrete models. The three-parameter model was used only for the purpose of comparison. The effect of preload was studied both in harmonic and transient loading. In addition, the effect of load rate was studied in transient loading. For comparing the results, the model parameters obtained through different test methods and loading conditions have been presented in terms of storage modulus and loss factor in the frequency domain.

The physical properties of the Kevlar-29 fabric tape under study and filament used for its construction are given in Tables 1 and 2.

Table 1
Specifications of Kevlar tape

Material	Kevlar-29 fibre
Type	Unidirectional woven fabric
Cross section	13 mm × 2.3 mm
Strength at break	20,000 N
Elongation at break	Less than 8%

Table 2
Typical physical properties of Kevlar-29 aramid filament (Lafitte and Bunsell, 1982; Yang, 1993)

Property	Value
Density (kg m^{-3})	1440
Strength (GN m^{-2})	2.6
Modulus (GN m^{-2})	62.0
Breaking strain (%)	4.2

2. Theory

2.1. Generalized standard linear model

For a perfectly elastic solid, in accordance with Hooke’s law, stress is always directly proportional to strain but independent of the rate of strain. However, for real materials there are two important types of deviations. First, the strain may not be directly proportional to the stress but may depend on stress in a more complicated manner. Second, the stress may depend on both the strain and the rate of strain together, as well as higher time derivatives of the strain. If only the latter is present, we have linear viscoelastic behaviour; then in a given experiment the ratio of stress to strain is a function of time alone, and not the stress magnitude (Ferry, 1970). The constitutive equation used in this study was based on linear viscoelasticity.

The generalized standard linear viscoelastic model is given in the following equation (Ahid Nashif et al., 1985):

$$\sigma + \sum_{n=1}^{\infty} \alpha_n \frac{\mathrm{d}^n \sigma}{\mathrm{d}t^n} = E\varepsilon + E \sum_{n=1}^{\infty} \beta_n \frac{\mathrm{d}^n \varepsilon}{\mathrm{d}t^n} \tag{1}$$

where σ is stress, ε is the strain, E is modulus of elasticity and t is time. Based on the above equation, an infinite series of stress derivatives and strain derivatives are required to represent the true viscoelastic behaviour of the material. The coefficients of this series are to be tailored to fit measured data. Obviously, an infinite series is too complex to handle. A truncated series meeting the desired accuracy is a more practical approach.

2.2. Discrete models

When any material exhibits linear viscoelastic behaviour, its mechanical properties can be duplicated by a model consisting of some suitable combination of springs which obeys Hooke’s law, and viscous dashpots which obey Newton’s law (Ferry, 1970). It can be seen that a discrete model with limited number of elements can represent a truncated series of Eq. (1).

Accurate prediction of the material response to various dynamic loads and deformation is dependent on the selection of an appropriate number of elements in the model, as well as the correct assignment of spring constants and viscosity values to these elements. When only a very few elements are involved in the model, calculations are relatively simple, but the agreement with the observed behaviour is usually poor, since the constant dashpot coefficient used implies far too rapid a variation of complex modulus properties with frequency (David Jones, 2001). With the