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A continuum damage model for glass/epoxy laminates in tension

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A B S T R A C T

The present work is concerned with the study of the damage behaviour of a composite material based on glass fibre reinforced polymer (GFRP). The main goal is to predict the rupture force using model equations that combine enough mathematical simplicity to allow their usage in engineering problems with the capability of describing a complex nonlinear mechanical behaviour. A model for tensile developed within the framework of Continuum Damage Mechanics that accounts for the effect of the load rate and temperature of the system is proposed and analyzed. The predicted values of tensile stress for different values of the load rate and temperature are compared with experimental data, showing a good agreement.

1. Introduction

Over the last decade, composite materials have been used to repair damaged gas and liquid transmission pipelines. Corrosion damage is one of the leading causes of transmission pipeline failures [1]. Because of the severity of this defect type, pipeline companies are required to respond to these anomalies by either removing damaged sections or repair using welded sleeves. Since in some fields (for instance, in offshore oil platforms) repair work cannot be performed using heat, composite materials gain a significant importance [2].

Composite materials have been used to repair corroded pipelines and their use has gained wide acceptance across the pipeline industry [2–4]. However, the mechanical responses of fibre-reinforced polymeric composites are sensitive to the rate at which they are loaded and temperature operation. In many technological applications, under dynamic loading conditions, the response of a structure designed with static properties might be too conservative. The main reason is that mechanical properties of composites vary significantly with changing the strain rate and temperature. Unlike metals, which have been studied extensively over a wide range of strain rates and temperatures, only limited amount of information is available on the effects of strain rate and temperature on the response of fibrous composites.

Many researchers studied composite materials at different strain rate and others have studied their behaviour at different temperature but few combined both.

The work performed by Rotem and Lifshitz [5] investigated the tensile behaviour of unidirectional glass fibre/epoxy composites over a wide range of strain rates from 10^{-6} to 30 s^{-1} and found that the dynamic strength is three times higher than the static strength and the dynamic modulus is 50% higher than the static modulus. However, while investigating angle ply glass/epoxy laminates, Lifshitz [6] found that the elastic modulus and failure strain were independent on the strain rate and the dynamic failure stress was only 20–30% higher than the static failure stress.

Tensile tests were performed on a glass epoxy laminate at different rates by Okoli and Smith [7–10] to determine the effects of strain rate on Poisson's ratio, shear, flexural and tensile properties of the material. Armenakas and Sciamarella [11] suggested a linear variation of the tensile modulus of elasticity of unidirectional glass/epoxy composites with the log of strain rate.

A systematic study of the strain rate effects on the mechanical behaviour of glass/epoxy angle ply laminates was done by Staab and Gilat [12,13]. Although both fibres and matrix are strain rate sensitive, the fibres were thought to influence laminate rate sensitivity more than the matrix.

To achieve the high performance required in the material's projected applications, a good understanding of the dynamic deformation of GFRP under different temperatures is essential. The present work is a continuation of the work begun in [14], in which tensile tests at different strain rates and temperatures were performed in glass fibre reinforced polymer (GFRP). It is observed that such kind of composite presents a rate dependent behaviour and that strain rate strongly affects the ultimate tensile strength whereas the modulus of elasticity is almost insensitive to it (a quasi-brittle behaviour, see [15,16]). In this paper, a simplified damage model

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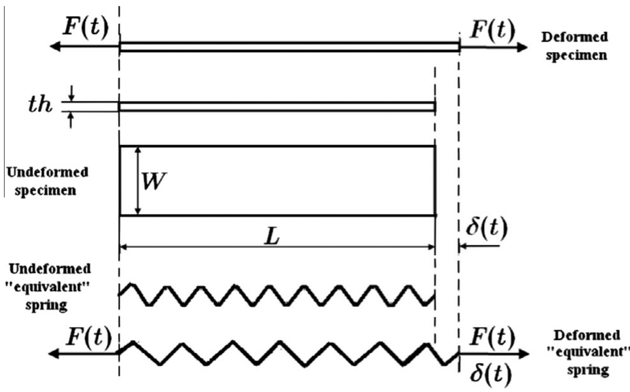

Fig. 1. Tensile specimen and equivalent spring system.

for GFRP specimens is proposed. The model is developed within the framework of Continuum Damage Mechanics and the constitutive equations can be derived from thermodynamic arguments and follow a procedure successfully used to model tensile tests in the presence of other nonlinear phenomena [17–20]. The goal is to propose model equations simple enough to allow their usage by designers while retaining the capability of describing a complex non-linear mechanical behaviour. The focus is to use this model to analyze the strength of a given specimen in tensile tests under different loading rates and temperatures. The thermodynamic framework adopted in the study is global and the local concepts of stress and strain are not used because the GFRP specimen is considered as a system. If adequate expressions are chosen for the free energy and energy dissipation of the system, it is possible to describe the stiffness of the joint.

The material constants considered in the constitutive equations are easily identified experimentally. Besides the model equations are simple from the mathematical point of view they can be solved analytically. The goal is to use such model to obtain as much information as possible about the influence of the loading rate and of the temperature. The basic idea behind the model is to approximate the stiffness K of the specimen subjected to tensile loading with a nonlinear "spring" with the same stiffness. This allows accounting for the nonlinear behaviour of the specimen (see Fig. 1).

Under a prescribed axial load $F(t)$ the system undergoes an elongation $\delta(t)$. The work of the external forces at any instant t is given by the product $F(t)\delta(t)$. In order to account for the dissipative mechanism of rupture, a macroscopic auxiliary damage variable $D \in [0,1]$, related to the loss of the global stiffness of the specimen due to the damage is introduced. Initially the specimen has a linear behaviour with stiffness K_o. If $D = 0$, the specimen is undamaged

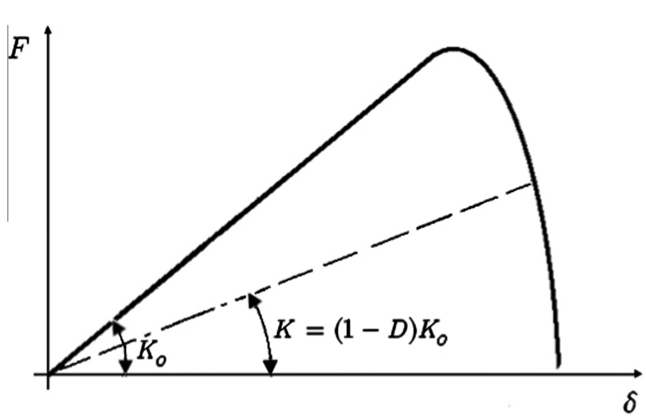

Fig. 2. Definition of the variable D during a tensile test.

($K = K_o$) and if $D = 1$, it is broken (it can no longer resist to mechanical loading $K = 0$). The evolution of the auxiliary variable D can be evaluated by using the relation $F = K\,\delta = (1 - D)K_o\delta$ and measuring the variable joint stiffness K in a tensile test (see Fig. 2). The force F that corresponds to an elongation δ on the "equivalent" spring is also supposed to obey the law $F = (1 - D)K_o\delta$. Hence, the modelling of the "equivalent" spring is reduced to define an adequate expression for the evolution of the damage variable D. The choice of the adequate expression is made within a thermodynamic context, and is discussed in the next section.

2. Materials and experimental procedures

The apparatus and procedure used to obtain the tensile properties in the GFRP laminates are described below.

Tensile tests were performed according to ASTM D3039 [21]. The test specimens were cut from hand lay-up sheets. The glass was a cross-ply plain weave e-glass [0/90°] fabric with 326 g/cm^2 weight. The composite had a fibre weight fraction of 70% with eight layers of glass. The epoxy resin system used was RR515 from SILAEX® based on a diglycidyl ether bisphenol A and an aliphatic amine hardener, being processed with a maximum mix ratio of 4:1 (with low viscosity). The resin systems properties provided by the manufacturers are presented in Table 1.

The specimens were cut 250 mm × 25 mm, leaving a gauge section of 200 mm. The tensile tests were performed on a Shimadzu AG-X tensile testing machine at three different rates: $\dot{\delta} = 0.2$ mm/min, $\dot{\delta} = 2.0$ mm/min and $\dot{\delta} = 20.0$ mm/min. Attached to the testing machine a thermostatic chamber was used to set the temperature test environment. The test temperatures used were: 20 °C, 40 °C, 60 °C and 80 °C. These temperatures were chosen since Heat Distortion Temperature is 50 °C, so tests were performed at HDT ± 30 °C. Five GFRP specimens have been used for each temperature and loading rate.

3. Results and discussion

3.1. Tensile tests

Figs. 3 and 4 present the curves $F \times \delta$ obtained in tensile tests performed at four different temperatures ($\theta = 20$ °C, $\theta = 40$ °C, $\theta = 60$ °C, $\theta = 20$ °C, $\theta = 80$ °C) and three loading rates ($\dot{\delta} = 0.2$ mm/min, $\dot{\delta} = 2.0$ mm/min, $\dot{\delta} = 20.0$ mm/min). For the lower temperatures ($\theta = 20$ °C, $\theta = 40$ °C, $\theta = 60$ °C) it is observed a quasi-brittle behaviour: the curve is linear until a brutal failure. The different behaviour for the tests performed at 80 °C is not surprising since DSC test made on the polymer matrix showed that glass transition temperature is at 65 °C and the Heat Distortion Temperature (HDT) is 50 °C.

It can be verified that the stiffness is strongly dependent of the temperature but it is not significantly affected by the loading rate. The rupture force F_{max} is dependent of both temperature and loading rate. The stiffness K_o measured at different temperatures is presented in Table 2. As expected, the stiffness decreases with

Table 1
Properties of the epoxy resin.

Property	Epoxy
Viscosity at 25 °C μ (cP)	12,000–13,000
Density ρ (g/cm^3)	1.16
Heat Distortion Temperature HDT (°C)	50
Modulus of elasticity E (GPa)	5.0
Flexural strength (MPa)	60
Tensile strength (MPa)	73
Maximum elongation (%)	4