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TENSILE BEHAVIOUR OF GLASS FIBRE REINFORCED POLIURETHANE AT DIFFERENT STRAIN RATES

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Abstract. *This paper is concerned with the modelling of the tensile behaviour of glass fibre reinforced polyurethane under variable strain rates. This particular composite has viscoelastic behaviour with both elasticity modulus and ultimate tensile strength being strongly dependent of the strain rate. It is proposed a one-dimensional viscoelastic phenomenological damage model able to perform a physically realistic description of the strain rate sensitivity. The aim is to predict the stress-strain behaviour at different strain rates using model equations that combine enough mathematical simplicity to allow their use in engineering with the capability of describing the mechanical behaviour. The materials parameters that appear in the model can be easily identified from only three tests performed at constant strain rates. Modelling prediction showed good agreement with experimental results.*

Keywords: *Glass Fibre Reinforced Polyurethane; Tensile tests; Viscoelasticity; Continuum damage mechanics.*

1. INTRODUCTION

In recent years it is observed a rapid growth in the development and application of fibre-reinforced thermoplastic polymer composites. Besides this significant growth, the need to better understands and measures the mechanical parameters, which control the structure–property relationships in such composites are mandatory. Polyurethane belongs to one of the most versatile classes of polymers and can exist as both thermosetting and thermoplastics depending upon the choice of the initial reactants. This family of polymers is a leading contender for several lightweight engineering applications. Polyurethanes have the advantage of having low viscosity, excellent bonding with the matrix material without special sizing of the fibres, relatively low price and fast reaction time. The polyurethanes are an important and very versatile class of polymer materials with desirable properties, such as high abrasion resistance; tear strength, excellent shock absorption, flexibility and elasticity (Chiou, *et al*., 2002; Desai, *et al*., 2000). The extensions of product life cycle and resource conservation are important environmental considerations that often favour the selection of polyurethanes (Wirpsza, 1993; Bayer, 1979).

The last few years has seen a rapid growth of resin impregnated fabric bandages, the most common being knitted fiberglass fabric impregnated with a polyurethane resin. The use of a continuous filament fiberglass to produce a fabric, which has the strength and flexibility for casting can be achieved by the selection of the appropriate glass fibre diameter and the pattern of the fabric knit. During manufacture the knitted fiberglass roll is impregnated with a urethane pre-polymer resin. The formulation of this pre-polymer resin contributes to the characteristics of the cured polyurethane and hence the properties of the final cast.

In the last few years some works have been performed by researchers on glass fibre reinforced polyurethane (GFRP). Saint-Michel, *et al*., (2006a; 2006b) studied the mechanical properties of polyurethane foam with different densities and filler size. Husic, *et al*., (2005) investigated the thermal and mechanical properties of two types of polyurethane resin, one commercial and another derived from soybean oil, reinforced with glass fibres. Both composites displayed excellent results showing that polyurethane from soybean oil is an alternative to petrochemical resin. Wilberforce, *et al*., (2009) studied the effect of fibre concentration, strain rate and weldline on mechanical properties of short glass fibre polyurethane composites. The long-term properties of polyurethane reinforced composites were investigated by Bruckmeier, *et al*., (2011) with the intention of using the composites in the automotive industry due to its lightweight, strength and damage tolerance.

With several advances made in understanding the behaviour of composite materials, GFRP are finding increasing use as primary load bearing structures and also in a wide range of high technology engineering applications, such as

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pipeline reinforcement. Therefore, high strain rate loading is probable in many of the applications where these composites find use as candidate materials (Jacob, *et al*., 2004). As a consequence, study of how mechanical properties of these composites would change with strain rate is warranted to be able to design structures (Menard, 1999). Increasing the strain rate leads to higher moduli because the polymer chains have reduced the relaxation time (Alkonis, *et al*., 1983). In very short time ranges, the molecules, not having sufficient time to reorient substantially, probably react to a stress by distorting intermolecular distances. These distortions being of a rather high energy result in a high modulus (Saunders, *et al*., 1962).

In this paper, a simplified damage model for pre-impregnated glass fibre reinforced polyurethane specimens is proposed. Since one of the main applications of such composite material is to repair and reinforce both internal and external corrosion on pipelines, the knowledge of the material behaviour when strain rate varies is crucial to execute an accurate and appropriate repair. Corroded pipelines with part-wall metal loss defects can be repaired or reinforced with a composite sleeve system. In these systems, a piping or vessel segment is reinforced by wrapping with concentric coils of composite material (da Costa-Mattos, *et al*., 2009).

The model is developed within the framework of Continuum Damage Mechanics. The constitutive equations can be derived from thermodynamic arguments and follow a procedure successfully used to model tensile tests in the presence of nonlinear phenomena (Reis, *et al*., 2012; da Costa Mattos, *et al*., 2012a). Such a thermodynamic approach is global and the local concepts of stress and strain are not used because the useful portion of the 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 specimen as described in Mattos (1995). Such a procedure aims at obtaining model equations that are simple enough to allow their usage by designers while retaining the capability of describing a complex non-linear mechanical behaviour.

In the present study, the focus is to use this approach to analyse the strength of a given specimen of glass fibre reinforced polyurethane in tensile tests under different strain rates. The material constants considered in the constitutive equations are easily identified experimentally. Besides, the model equations are simple from the mathematical point of view and can be solved analytically.

2. MATERIALS AND METHODS

2.1 Materials

Polyurethane reinforced composites are widely used in various applications ranging from medical devices to automotive body panels. The success of polyurethane is due to its ability to be produced in various forms from flexible to rigid structures (Saunders, *et al*., 1962; Szycher, 1999). In this research polyurethane pre-impregnated, bi-directional E-glass fibre composite used to repair and reinforce internal and external corrosion on pipeline or structures is used to evaluate its performance at different strain rate. This composite is a commercial product from Neptune Research Inc. (NRI) called Syntho-Glass XT®. This product is water-activated polyurethane resin, which reduces composite preparation time in 50%. It can be installed in wet, rainy or submerged environments. According to manufacturer gel time is 30 minutes and it is fully cured after 2 hours at 24ºC. Service temperature range from -46ºC to 90ºC and it can be applied in environment conditions from 4ºC to 65ºC. The thermal behaviour of the composite was measured with a differential scanning calorimetric, DSC F3-MAIA Netzsch®, under nitrogen atmosphere. The samples were heated at a rate of 20ºC/min from 10 to 500 ºC. Figure 1 presents the DSC analysis of the studied composite.

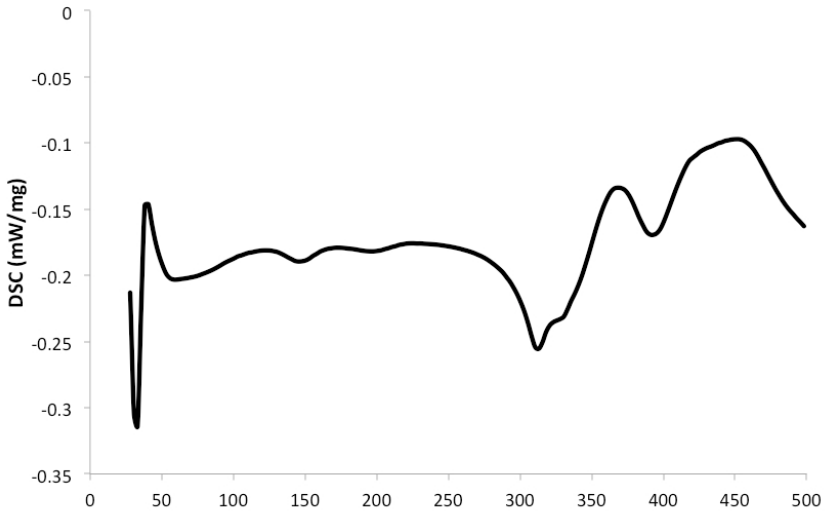

Figure 1. Glass fibre reinforced polyurethane DSC test result

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From Fig. 1 it can be seen that this composite has a glass transition temperature of 133ºC, melting at 312ºC and oxidation at 432ºC. Composite repair standards such as ISO TS24817 (ISO/TS 24817, 2006) and ASME PCC-2 (ASME PCC-2, 2011) recommends the maximum service temperature is T*g* – 30ºC. From DSC results the maximum service temperature will be 103ºC, which it is well covered according to manufacturer.

2.2 Methods

Tensile specimens were hand lay-up manufactured. Each Syntho-Glass XT® pre-pag sheet has 0.33 mm and 15 layers were laminated to produce a 5 mm thickness plate. After curing fully cured after 2 hours at 24ºC, coupons were water jet cutted in 250 mm x 25 mm. Specimens were measured and friction tabs, essentially nonbonded tabs held in place by the pressure of the grip, emery cloth were used between the machine grip and the specimens. Syntho-Glass XT® composites were tested in tension at 23°C in a Shimadzu AGX-100 universal testing machine according to ASTM: D3039/D3039M-08. Tests were performed at crosshead displacement rates of 0.2, 1, 2, 10 and 20 mm/min giving nominal strain rate values of 2 x 10^{-5}, 1 x 10^{-4}, 2 x 10^{-4}, 1 x 10^{-3} and 2 x 10^{-3} s^{-1}, respectively. For the tested material, five specimens were tested at a given rate. The stress–strain curve for each specimen was recorded using an electrical strain gauge glued to the specimen. Tensile modulus was obtained from the initial slope of the stress–strain curve and the tensile strength from the maximum load.

3. RESULTS AND DISCUSSION

3.1 Tensile tests

Figure 2 presents the tensile stress vs. strain curves for glass fibre reinforced polyurethane obtained from the tensile tests performed with controlled strain rates: $\dot{\varepsilon}_1 =$ 2 x 10^{-5} s^{-1}, $\dot{\varepsilon}_2 =$ 1 x 10^{-4} s^{-1}, $\dot{\varepsilon}_3 =$ 2 x 10^{-4} s^{-1}, $\dot{\varepsilon}_4 =$ 1 x 10^{-3} s^{-1} and $\dot{\varepsilon}_5 =$ 2 x $10^{-3}s^{-1}$.

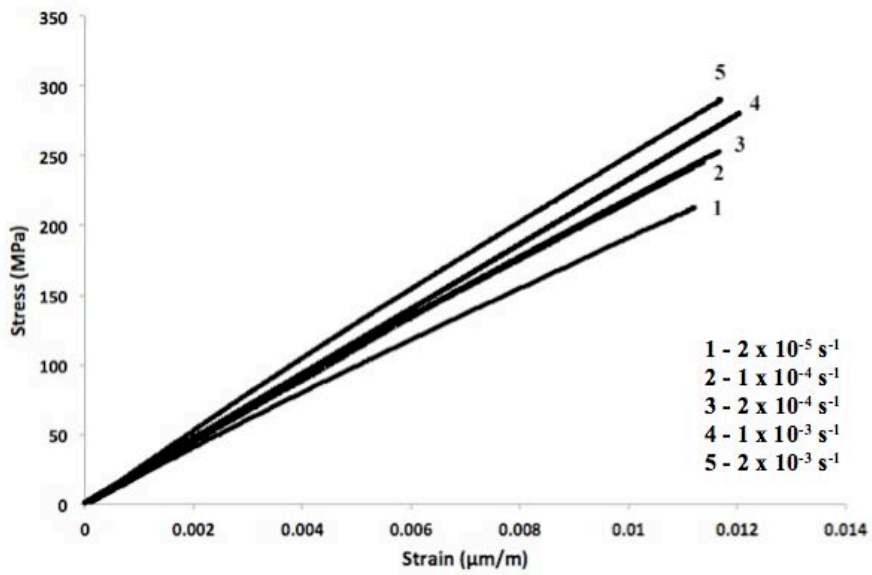

Figure 2. Stress vs. strain experimental curves at different strain rates

The behaviour is linear until a brutal rupture. Nevertheless, both elasticity modulus and ultimate strength are strongly rate-dependent (they tend to be higher for higher strain rates). Similar behaviour is also observed in other composite materials previously studied (Reis, *et al*., 2012).

3.2 Modelling

A slight non homogeneity in a pre-impregnated glass fibre reinforced polyurethane specimen may strongly affect stress and strain fields and a local analysis may be inadequate to predict its strength. Hence, a global phenomenological modelling with a few parameters to account for the rate dependency may be, eventually, a reasonable alternative. In this paper, a simplified damage model for single lap joints adhesion specimens is proposed.

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This model is conceived for a given range of strain rates $\dot{\varepsilon}_{\min} \le \dot{\varepsilon} \le \dot{\varepsilon}_{\max}$. It is difficult to present a precise definition of the limiting strain rates $\dot{\varepsilon}_{\min}$ and $\dot{\varepsilon}_{\max}$. In the absence of a precise physical definition, it is suggested that a range from $2x10^{-5}$ s^{-1} to $2x10^{-3}$ s^{-1} be considered for the strain rate.

The present analysis considers a single specimen with gauge length *L* and cross-section *A* under tension submitted to a prescribed elongation $\delta(t)$. $F(t)$ is the tensile force applied at the extremities. The thermodynamic framework adopted in the study is global and the 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 focus is to use this model to analyse the influence of stain rate in the strength in a tensile test. Therefore, the equations only allow to access those macroscopic quantities (forces and elongation) and the variables $\sigma(t) = F(t) / A$, $\varepsilon(t) = \delta(t) / L$, an $D(t) = 1 - \sigma(t) / \left[E(\varepsilon(t)\right] = 1 - \left[F(t)L_o\right] / \left[EA_o(\delta(t) - \delta_p(t)\right]$ must be interpreted as global parameters - they are not the "real" stress, strain and damage fields in the specimen undergoing stress corrosion (da Costa-Mattos, *et al*., 2008).

Initially, it is experimentally observed that the curve σ x ε is linear. After a given stress σ^* (or, its equivalent, after an energy $\Psi = (\sigma^*)^2 / 2E$ is reached), the damage becomes important and the behaviour is no longer linear (see Fig. 3) (Costa-Mattos, *et al*., 2010; da Costa Mattos, *et al*., 2012a).

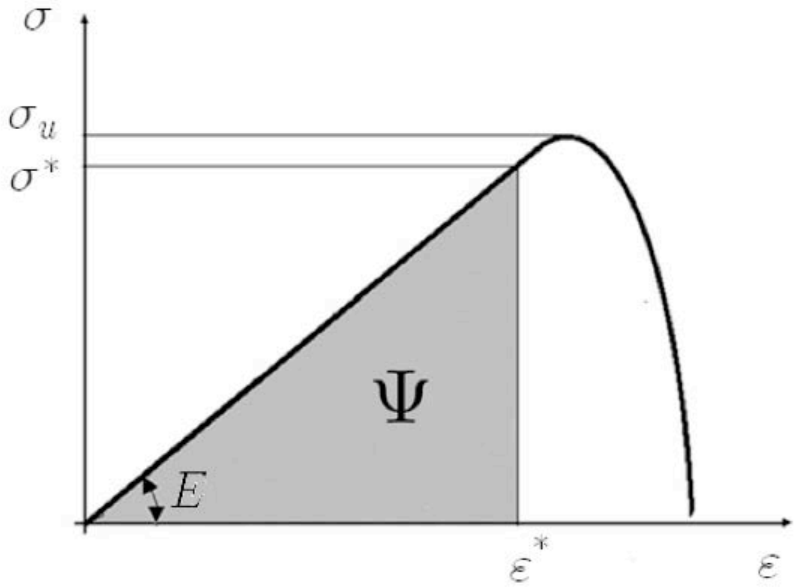

Figure 3. Experimental identification of the energy Ψ in a tensile test

The choice of the adequate expression for the evolution law for this global damage variable is made within a thermodynamic context. It is supposed that the system is governed by the following model equations:

$$\sigma = (1 - D)E\varepsilon \tag{1}$$

$$\dot{D} = \frac{1}{c}\left\langle G - \Psi \right\rangle; \quad D(t = 0) = 0; \quad 0 \le D \le 1 \tag{2}$$

With

$$\left\langle G - \Psi \right\rangle = \max\{(G - \Psi), 0\} \tag{3}$$

$$G = \frac{1}{2}E\varepsilon^2; \quad \Psi = \frac{1}{2}\frac{(\sigma_u)^2}{E} \tag{4}$$

$$E = k(\dot{\varepsilon})^n, \quad \sigma_u = (a(\dot{\varepsilon})^b) \tag{5}$$

k, n, a and b are positive parameters. The identification of these parameters is discussed in the next section. Equations (1) - (5) form a complete set of governing equations.

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The initial value problem formed by Eqs. (1-5) with a prescribed elongation $\varepsilon(t) = \alpha t$ $(\alpha > 0)$ can be solved analytically. In this case, it is possible to verify from Eq. (2) that:

$$D = 0 \text{ if } G = \frac{1}{2} E\varepsilon^2 \leq \Psi \tag{6}$$

Hence:

$$D = 0 \text{ if } \varepsilon < \varepsilon^* = \sqrt{\frac{2\Psi}{E}} \tag{7}$$

The deformation ε^* is reached at instant $t^* = (\varepsilon^* / \alpha)$. The stress $\sigma^* = \sigma(t^*)$ beyond which the curve $\sigma \times \varepsilon$ is no longer linear is given by the following expression:

$$\sigma^* = E\varepsilon^* = E\sqrt{\frac{2\Psi}{E}} \Rightarrow \Psi = \frac{(\sigma^*)^2}{2E} \tag{8}$$

The damage variable is equal to zero until this limit is reached. Considering a prescribed deformation $e < (R/10)\ \varepsilon(t) = \alpha t$ $(\alpha > 0)$, it is possible to verify that, after instant t^*, the damage increases until rupture ($D = 1$) at instant t^r. Thus the solution of Eq. (2) for $t^r \in [t^*, t^r]$ is

$$D(t) = \frac{1}{c}\left[\frac{1}{6} E\alpha^2[t^3 - (t^*)^3] - \Psi[t - t^*]\right] \tag{9}$$

Figure 4 presents the influence of the constant c in the curve $\sigma \times \varepsilon$.

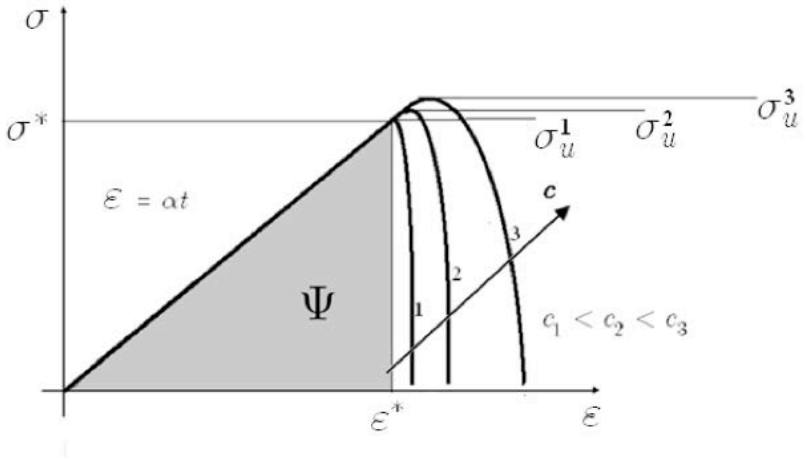

Figure 4. Influence of c in the specimen behaviour

Constant c is related to the viscosity of the material and can be identified from one rupture test using Eq. (9) and the condition $D\ (t = t^r) = 1$:

$$c = \left[\frac{1}{6} E\alpha^2[(t^r)^3 - (t^*)^3] - \Psi[t^r - t^*]\right] \tag{10}$$

In general, c is very small. If $c \to 0$, $t^r \to t^*$, $\varepsilon^r \to \varepsilon^*$ and $\sigma^* \to \sigma_u$. Hence, in this case, the material does not present significant rate dependency and the behaviour is brittle. Equations (1, 2) allow describing the rate dependency, as shown schematically in Fig. 5.

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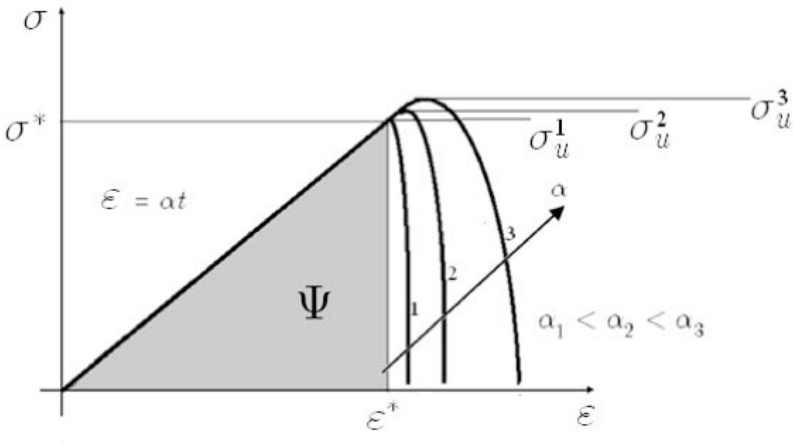

Figure 5. Rate dependency

3.3 Comparison with experimental results

Figure 6 presents the comparison between experiments and model prediction considering the following parameters a = 35155 MPa, b = 0.0554, c= 10-3, k = 36.69 GPa n = 0.0543.

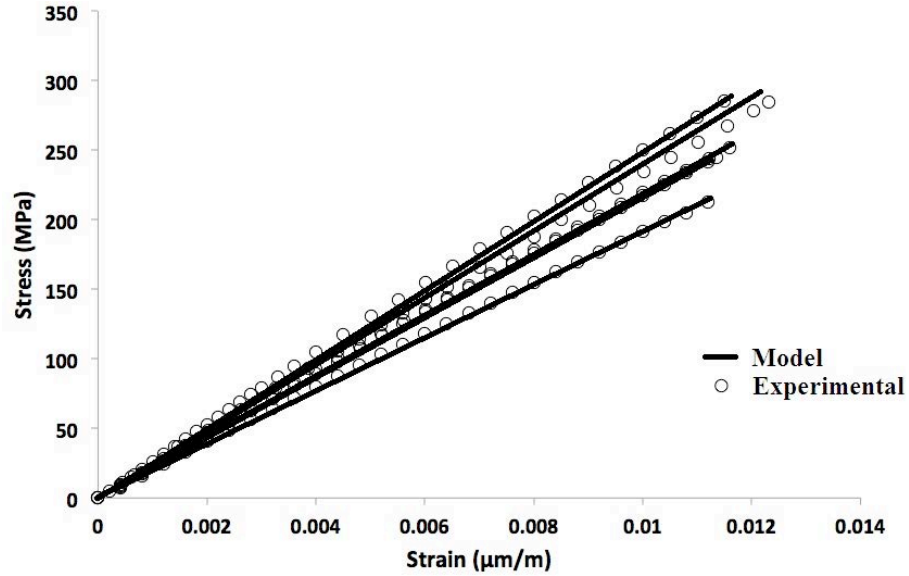

Figure 6. Tensile stress-strain curves obtained at different strain rates. Comparison with experimental results.

According to Fig. 6 it can be seen that the model predicts with good agreement the tensile behaviour of glass fibre reinforced polyurethane at different strain rates.

Table 1 presents the experimental and predicted modulus of elasticity and Tab. 2 presents the experimental and predicted ultimate tensile strength.

Table 1. Modulus of elasticity. Experimental and model prediction

Strain rate(s^{-1})	Modulus of Elasticity (GPa)		
	Experimental	Model	% Variation
0.00002	20.38 ± 1.22	20.46	+ 0.39
0.0001	22.34 ± 0.98	22.31	- 0.13
0.0002	23.46 ±1.03	23.17	- 1.24
0.001	24.90± 1.37	25.27	+ 1.49
0.002	26.41 ± 1.73	26.23	- 0.68

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From Tab. 1 it can be seen that the experimentally obtained modulus of elasticity is close to the analytical prediction for the entire strain rate range considered. Values are lower than 2% difference.

Table 2. Ultimate Tensile Strength. Experimental and model prediction

Strain rate(s^{-1})	Ultimate Tensile Strength (MPa)		
	Experimental	Model	% Variation
0.00002	213.36 ± 1.26	216.77	+ 1.60
0.0001	245.58 ± 1.34	240.15	- 2.21
0.0002	253.08 ± 1.77	255.96	+ 1.14
0.001	284.46 ± 3.06	295.34	+ 3.82
0.002	290.42 ± 2.45	291.38	+ 0.33

Low variation between the experimental ultimate tensile strength and model predict is observed according to Tab. 2. For such comparison, values under 4% are reported.

The proposed Eqs. (1-5) can be used to obtain a simple criterion for gloves used as reinforcement systems in a pipe with inner radius R and wall thickness e simply by replacing the axial stress and axial strain ($\sigma = F/A$ and $\varepsilon = \delta/L$) by the circumferential stress and strain components (respectively $\sigma_\theta = (PR/e)$ and $\varepsilon_\theta = \delta_R / R$ (R is the inner radius and e the wall thickness). Such approximation is very good provided $e < (R/10)$ (da Costa Mattos, *et al*., 2012b).

$$E = k(\dot{\varepsilon})^n,\ P_u = \frac{e}{R}(a\ (\dot{\varepsilon}_\theta)^b)\varepsilon_\theta$$

4. CONCLUSIONS

Quasi-static and high strain rate tensile tests were performed on glass fibre reinforced polyurethane. The experimental analysis shows that the mechanical response of this composite is strongly strain rate dependent. The modulus of elasticity increases with the strain rate and higher ultimate strengths are obtained for higher strain rates. The proposed one-dimensional constitutive equations allow describing with good agreement the experimental results. They predict very well the modulus of elasticity and the ultimate strength at different strain rates. This study is a preliminary step to obtain a simple but effective failure criterion for composite reinforcement systems used for corroded pipelines in oil industry.

5. ACKNOWLEDGEMENTS

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