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Analysis of a glass fiber reinforced polyurethane composite repair system for corroded pipelines at elevated temperatures

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ABSTRACT

The repair of corroded pipelines with fiber reinforced polymer (FRP) matrix composite overwrap systems is a well-developed practice in the oil and gas transportation industry. The FRP repair system also slows the external corrosion growth rate by shielding the damage from the environment while the pipeline stays in service. Laboratory hydrostatic burst tests and field practice of several years have shown that these repairs are effective for pipelines with external corrosion defects. In order to evaluate the effectiveness of a given repair system it is common to first manufacture a defect into a pristine pipe specimen, then secondly repair the damaged region, and finally pressurize the pipe monotonically until failure occurs. The size and shape of the defect region can have a significant effect on the level of repair that can be achieved. The present paper is concerned with the analysis of epoxy repair systems for metallic pipelines undergoing elastic or inelastic deformations with localized corrosion damage that impair the serviceability. The main motivation for the study presented in this paper is the rehabilitation of corroded pipelines conveying produced water in offshore oil platforms. Although the operating pressure of these pipelines is not very high, the water temperature is between 60^{o}C to 90^{o}C, which can be a major shortcoming for the use of polymeric material as repair systems.

Keywords: Glass Fiber Reinforced Polyurethane; Tensile tests; Temperature; Pipeline Repair Systems.

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 fibers, relatively low price and fast reaction time. The polyurethanes are an important and a very versatile class of polymer materials with desirable properties, such as high abrasion resistance; tear strength, excellent shock absorption, flexibility and elasticity [1-3]. The extensions of product life cycle and resource conservation are important environmental considerations that often favor the selection of polyurethanes [4-6].

The last few years have 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 fiber diameter and the pattern of the fabric knit. During manufacture the knitted fiberglass roll is impregnated with a urethane resin. The formulation of this 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 fiber reinforced polyurethane (GFRP). Saint-Michel et al. [7,8] studied the mechanical properties of polyurethane foam with different densities and filler size. Husic et al. [9] Investigated the thermal and mechanical properties of two types of polyurethane resin, one commercial and another derived from soybean oil, reinforced with glass fibers. Both composites displayed excellent results showing that polyurethane from soybean oil is an alternative to petrochemical resin. Wilberforce and Hashemi [10] studied the effect of fiber concentration, strain rate and weld line on mechanical properties of short glass fiber polyurethane composites. The long-term properties of polyurethane reinforced composites were investigated by Bruckmeier and Wellnitz [11] 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 behavior 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 pipeline reinforcement. Therefore, high strain rate loading is probable in many of the applications where these composites find use as candidate materials [12]. As a consequence, the study of how the mechanical properties of these composites would change with strain rate is warranted to be able to design structures [13]. Increasing the strain rate leads to higher moduli because the polymer chains have reduced the relaxation time [14]. 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 [15].

In [16], a simplified damage model for pre-impregnated glass fiber 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 behavior when the 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 [17].

In the present paper, the study is concerned with the analysis of epoxy repair systems for metallic pipelines undergoing elastic or inelastic deformations with localized corrosion damage that impair the serviceability. The main motivation for the study presented in this paper is the rehabilitation of corroded pipelines conveying produced water in offshore oil platforms. Although the operating pressure of these pipelines is not very high, the water temperature is between 60^{o}C to 90^{o}C, which can be a major shortcoming for the use of polymeric material as repair systems. In the analysis, it is considered the same commercial pre-impregnated bi-directional polyurethane - fiberglass composite studied in [16]. Experimental results performed at the Laboratory of Theoretical and Applied Mechanics (tensile tests and hydrostatic tests) allow a better understanding of how the material elastic properties and strength varies with temperature within this temperature range. The focus is to use this approach to analyze the strength of a given specimen of glass fiber reinforced polyurethane in tensile tests under different temperatures. The main feature of such composite is that although the mechanical strength of the material decreases with temperature, the elastic properties do not vary within this temperature range. Therefore, the same methodology proposed in [17] allows obtaining the necessary thickness of the composite sleeve to assure the safe operation of corroded pipelines with arbitrary part-wall metal loss defects at temperatures up to 90°C.

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 [15, 18]. In this research polyurethane pre-impregnated, bi-directional E-glass fiber composite used to repair and reinforce internal and external corrosion on pipeline or structures is used to evaluate its performance at different temperatures. 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 environmental conditions from 4ºC to 65ºC.

2.2 Methods

Tensile specimens were hand lay-up manufactured. Each Syntho-Glass XT® pre-preg sheet has 0.33 mm and 15 layers were laminated to produce a 5 mm thickness plate. After curing fully curing after 2 hours at 24ºC, coupons were water jet cut 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 four different temperatures (20°C, 55°C, 71° C, 90°C) in a Shimadzu AGX-100 universal testing machine according to ASTM: D3039/D3039M-08. Tests were performed at crosshead displacement rates of 2 mm/min giving nominal strain rate value of 2 x $10^{-4}s^{-1}$. For the tested material, five specimens were tested at a given temperature. 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 of the maximum load.

3 RESULTS AND DISCUSSION

3.1. DSC analysis

The thermal behavior of the composite was measured with a differential scanning calorimetry, 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.

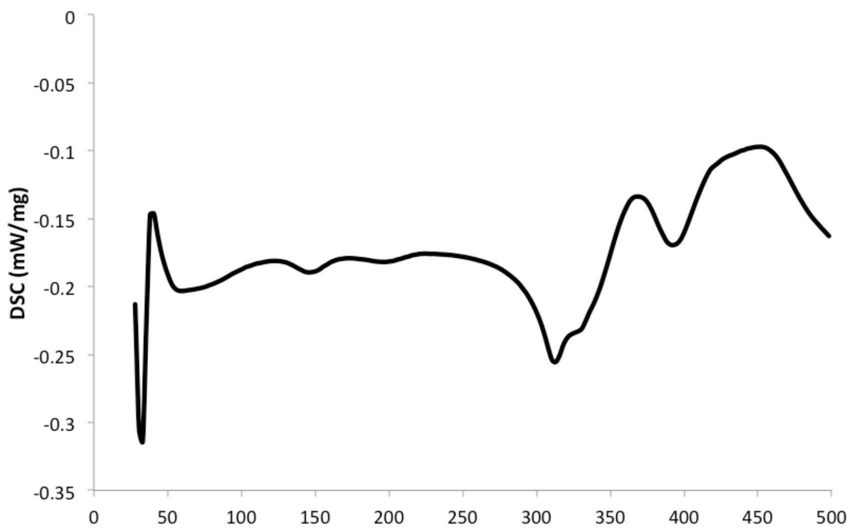

Figure 1: Glass fiber reinforced polyurethane DSC test result

From figure 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 [19] and ASME PCC-2 [20] recommends the maximum service temperature is Tg – 30ºC. From DSC results the maximum service temperature will be 103ºC, which it is well covered according to the manufacturer.

3.2 Tensile tests

Figure 2 presents the tensile stress vs. strain curves for glass fiber reinforced polyurethane obtained from the tensile tests performed at different temperatures. It is observed a very small variation of the elasticity modulus, but the ultimate strength is strongly temperature-dependent (it tends to be higher for lower temperatures. Table 1 presents the average values of the ultimate stress obtained for the four different temperatures.

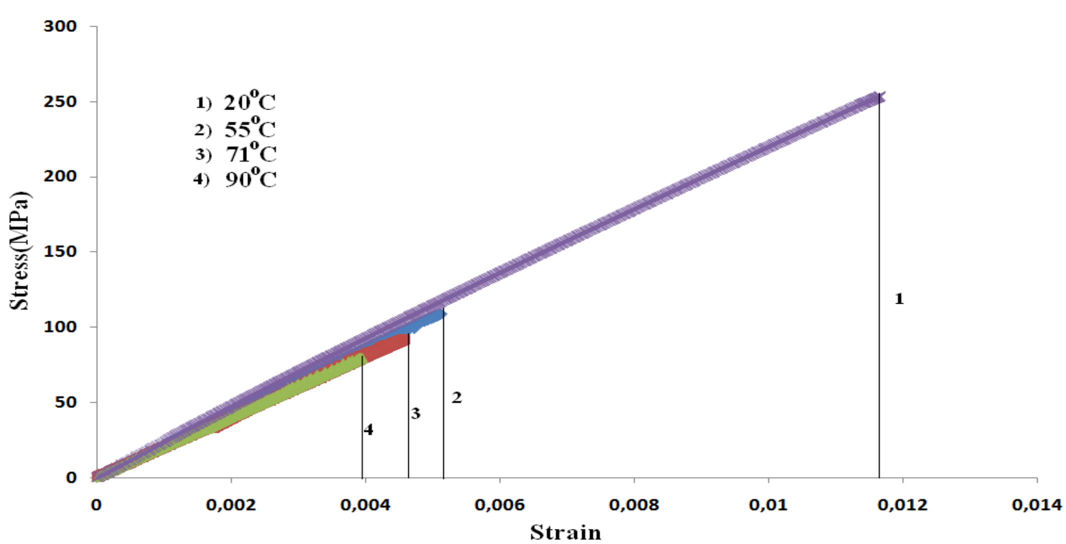

Figure 2: stress vs. strain at different temperatures.

It is observed a very small variation of the elasticity modulus, but a strong variation of the ultimate stress. Table 1 presents the average values of the ultimate stress obtained for the four different temperatures.

Table 1: Average values of the ultimate stress

Temperature ^{o}C	Ultimate Stress (MPa)
20	253.08
55	108.788
71	91.54
90	79.37

The following expression provides an adequate correlation between ultimate strength σ_u and temperature θ

$$\sigma_u = \alpha\theta^{\beta} \text{ with } \alpha\text{=2557MPa and } \beta = -0.78 \tag{1}$$

Figure 3 shows both the experimental and predicted ultimate strength.

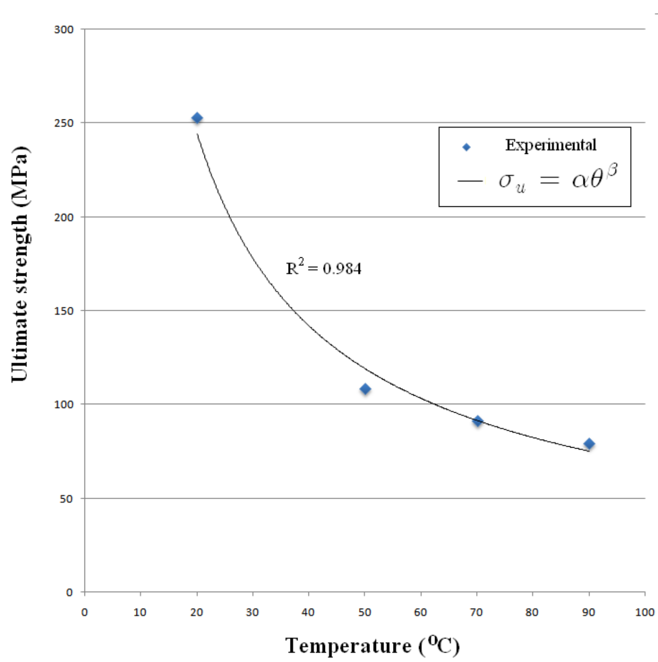

Figure 3: Ultimate strength. Experiment and prediction.

With eq. (1), the damage model proposed in [16] can be adapted to account for temperature variation.

$$\sigma = (1 - D)E\varepsilon \tag{2}$$

$$\dot{D} = \frac{1}{c}\left\langle G - \Psi \right\rangle; \quad D(t=0) = 0; \quad 0 \leq D \leq 1 \tag{3}$$

With

$$\left\langle G-\Psi\right\rangle = \max\{(G-\Psi),0\} \tag{4}$$

$$G=\frac{1}{2}E\varepsilon^2; \quad \Psi=\frac{1}{2}\frac{(\sigma_u)^2}{E} \tag{5}$$

$$E=k(\dot{\varepsilon})^n,\ \sigma_u=\alpha(\theta)^\beta \tag{6}$$

E, c, k, n, α and β are positive parameters. The only different expression is the one proposed for the ultimate strength. It is not the goal of the present paper to perform a discussion about such a damage model. These constitutive equations can be derived from thermodynamic arguments and follow a procedure successfully used to model tensile tests in the presence of nonlinear phenomena [21-24].

This kind of composite can be used as a composite sleeve reinforcement system for metallic pipelines undergoing elastic or inelastic deformations with localized part-wall metal loss that impairs the serviceability. The basic idea of the reinforcement technique is to transfer the hoop stress in the pipe wall due to the internal pressure to the composite sleeve. In the case of corroded pipelines conveying liquids the main difficulty is the definition of the adequate composite thickness to assure a satisfactory level of structural integrity. The methodology proposed in [17] to define the minimum thickness of composite material to assure the safety of repairs under operating conditions and/or the lifetime extension under operation conditions can be immediately applied. Such methodology, although simple, is able to account for different failure mechanisms (plasticity, corrosion, etc.). The additional information provided by the present study is a failure criterion for the composite sleeve (the hoop stress must be lower than the ultimate strength $\sigma_u=\alpha(\theta)^\beta$) that can eventually fail before the damaged pipe.

4 CONCLUSION

Tensile tests were performed on glass fiber reinforced polyurethane at different temperatures between room temperature and 90°C. The experimental analysis shows that the ultimate strength of this composite is strongly temperature dependent within this temperature range, while the elastic properties are not affected. This study is a preliminary step to obtain a simple but effective failure criterion for composite reinforcement systems used for corroded pipelines in the oil industry.

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