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

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ABSTRACT

The present paper is concerned with the analysis of glass fibre reinforced polyurethane repair systems for metallic pipelines with localised 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 and 90°C, which can be a major shortcoming for the use of polymeric material as repair systems. Tensile tests were performed to analyse the temperature dependence of a polyurethane pre-impregnated, bi-directional E-glass fibre composite. Burst tests were carried out to evaluate the performance of composite reinforcements applied to defects machined in pipeline test specimens. Preliminary ideas for a methodology to estimate the failure pressure of a reinforced specimen with arbitrary localised corrosion damage are presented.

1. Introduction

In recent years, it is observed a rapid growth in the development and application of fibre-reinforced thermoplastic polymer composites, which are often used to reinforce corroded metallic pipelines. 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 with desirable properties, such as high abrasion resistance; tear strength, excellent shock absorption, flexibility and elasticity [1–3], 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 cost and quick reaction time. The extensions of product life cycle and resource conservation are important environmental considerations that often favour 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 fibreglass fabric impregnated with a polyurethane resin. The use of continuous filament fibreglass 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 fibreglass 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.

Over recent years, studies have been performed by researchers on glass fibre 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 fibres. 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 fibre concentration, strain rate and weld line on mechanical properties of short glass fibre 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.

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. The rehabilitation of

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corroded pipelines with fibre reinforced polymer (FRP) matrix composite overwrap systems is becoming a well accepted engineering practice and an interesting alternative to the classical repair methods for metallic pipes, mainly in the oil industry, saving time and allowing safer operations [12–15]. The FRP repair system also slows the external corrosion growth rate by shielding the damage from the environment while the pipeline continues in service. In these repair systems, a piping or vessel segment is reinforced by wrapping it with concentric coils of composite material after the application of polymer filler in the corrosion defect. No matter the application procedure, 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. From the safety point of view, it is important to specify an adequate sleeve in order to guarantee a given maximum hoop stress criterion in the pipe [16].

Since one of the main applications of such composite material is to repair and reinforce both internal and external corrosion on pipelines, an adequate understanding of the mechanical behaviour is of utmost importance is crucial to execute an accurate and appropriate repair. One of the main issues is the possible variation of the mechanical properties of these composites with strain rate [17,18] and temperature. Increasing the strain rate leads to higher moduli because the polymer chains have reduced the relaxation time [19]. 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 [20]. In [18], a simplified damage model for pre-impregnated glass fibre reinforced polyurethane specimens is proposed.

In the present paper, the study is concerned with the analysis of glass fibre reinforced polyurethane repair systems for metallic pipelines with localised 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 and 90 °C, which can be a major shortcoming for the use of polymeric material as repair systems. The same commercial pre-impregnated bi-directional polyurethane–fibreglass composite studied in [18] is considered in the analysis. The focus now is on the analysis of the temperature effect on the material behaviour. Tensile tests and hydrostatic tests allow a better understanding of how the composite elastic properties and strength varies with temperature within this temperature range.

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. Thus, the same methodology proposed in [16] allows obtaining the necessary thickness of the composite sleeve to ensure the safe operation of corroded pipelines with arbitrary part-wall metal loss defects at temperatures up to 90 °C. Burst tests were carried out to evaluate the performance of composite reinforcements applied to defects machined in pipeline test specimens. Preliminary ideas for a methodology to estimate the failure pressure of a reinforced specimen with arbitrary localised corrosion damage are presented. The comparison of theory with experiment shows a very satisfactory correlation, which gives added confidence in using such a simple methodology in practical engineering situations.

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 [20,21]. In the present study, a polyurethane pre-impregnated, bi-directional E-glass fibre composite used to repair and reinforce internal and external corrosion on pipeline or structures was considered. This product is water-activated polyurethane resin, which reduces composite preparation time by 50%. According to the manufacturer, gel time is 30 min and it is fully cured after 2 h at 24 °C. Service temperature range from −46 to 90 °C and it can be applied in environmental conditions from 4 to 65 °C. Further technical data about this composite are presented in Table 1.

A steel pipe with wall loss, reinforced with this polyurethane composite repair, was also analysed. The pipe material is an API 5L X65 steel with the following basic properties: Youngś Modulus $E_{pipe} = 210$ GPa; yield stress $\sigma_y = 450$ MPa and ultimate strength $\sigma_u = 627$ MPa. The API-5L X65 grade steel is one of the most common pipeline materials in oil industry.

2.2. Methods

2.2.1. Tensile tests

Tensile composite specimens of the composite were hand lay-up manufactured. Each composite sheet has 0.33 mm thickness and 15 layers were laminated to produce a 5 mm thickness plate. After fully cured, 2 h at 24 °C, coupons were water jet cut in 250×25 mm. The specimens were tested in tension at four different temperatures (20, 55, 71, and 90 °C, five specimens per temperature) in a Shimadzu AGX-100 universal testing machine according to ASTM D3039/D3039M-08 [22] (see Fig. 1).

A crosshead displacement rate of 2 mm/min was adopted giving a nominal strain rate of $2 \times 10^{-4}\ \mathrm{s}^{-1}$. The stress–strain curve for each specimen was recorded using an electrical strain gauge glued to the specimen.

2.2.2. Hydrostatic tests

Hydrostatic tests with water at 80 °C were performed in metallic pipelines with localised part-wall metal loss reinforced with composite sleeve repair systems. Such kind of test is normally conducted under industry and/or customer requirements or specifications. They are performed to assess information about the effectiveness of a given repair or reinforcement system in a damaged pipeline. For experimental studies, rectangular regions with reduced wall thickness are artificially created in the specimens. In general, firstly temperature is raised up to a given fixed level and then pressure is applied. Hydrostatic tests at higher temperatures range may be performed using a pool with hot water in which the specimen in immersed or a system especially designed for this procedure in which the whole system (including the electrical resistance) is threaded at one extremity of the specimen (see [16]).

In the present study, an 18″ API 5L X65 pipe with 70% wall loss reinforced with the polyurethane composite repair system following the requirements of Annex C of ISO TS 24817 [23] was analysed. The pipe was prepared for testing by machining the defect

Table 1
Composite composition.

Component	% Composition
Fibreglass cloth (textile grade)	65–70
Fibrous glass dust	Not known (depend on method of handling)
Polyurethane prepolymer	15–18
Diphenylmethane diisocyanate	10.8–14.7
Titanium dioxide	0.7–1.4
P-Toluenesulfonyl isocyanate	0.4–1.1
Siloxane	0.4–1.1