Composite Structures 133 (2015) 312–321

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

The flexural properties of composite repaired pipeline: Numerical simulation and experimental validation

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ARTICLE INFO

Article history:
Available online 23 July 2015

Keywords:
Carbon fibre
Prepreg
Directional orientation
Finite element analysis (FEA)
Scale modelling

ABSTRACT

The performance of steel riser repaired with fibre reinforced polymer composite (FRPC) subjected to bending load was evaluated. Finite element (FE) analysis was used to simulate the load–strain behaviour of the repaired system. Accuracy of the model was validated against a simplified four-point bending experiment which was scaled to a significantly smaller size. The parameters investigated within the FE simulation and experimental tests are based on three conditions of the pipe riser – uncorroded, corroded and corroded repaired with designated laminate orientation of carbon/epoxy (C/E) FRPC. Design conditions were determined via a limit analysis known as the double-elastic slope method. The developed FE models based on flexural stiffness was found capable of predicting the same trend of strength improvements as the scaled-down testing of the corroded pipes repaired with different laminate orientation.

1. Introduction

In offshore operations, risers are part of the main component used to transport oil from the mudline to the surface [1]. Risers are susceptible to several types of mechanical loading, where the major load being pressure exerted by fluid content within the riser itself. Being submerged under water, risers are subjected to additional bending forces due to platform motion, wave forces and current. A predetermined amount of tensile force is frequently applied on the riser through buoyancy modules and top tensioning systems to alleviate buckling and excessive bending stress [2]. These subsea risers are exposed to a corrosive environment which causes degradation on its internal and external surfaces, manifested as loss in wall thickness along with deterioration of the performance and functionality over time. Rehabilitation of a riser with corrosion defects has relied on a repair sleeve that wraps around the corroded section of the pipeline, generally consisting of a conventional steel clamp and the more advance composite repair system (CRS) employing fibre reinforced polymer composite (FRPC). The CRS offers several distinct advantages over conventional steel clamp, such as light weight, high specific strength, good thermal insulation, excellent corrosion resistance, high fatigue performance and the capability for on-site repair without shutting down the live pipe, as hot welding work employed in the conventional steel clamp repair method can be eliminated. In recent years, the effectiveness of composite repair systems were evaluated for rehabilitation of mainly onshore pipeline, with studies led by companies such as Stress Engineering Inc [3], Kiefner and Associates Inc [4], and Gaz de France [5]. Most of these past researches [6–8] on CRS utilised both numerical modelling and experimental approaches.

The literature revealed that research related to optimisation of the CRS for subsea applications on steel risers are scarce. The authors' work focuses on CRS which utilises pre-impregnated FRPC that is more readily applicable to an automated wrapping machine to facilitate underwater wrapping. The optimisation of repair parameters such as types of reinforcement and fibre orientation was considered within the developed FE models [9,10].

With respect to the experimental approach, full-scale testing often provided the capability to fully represent the behaviour of the respective design and results obtained can be used directly to validate the accuracy of the numerical model. In the work of Deull et al., full scale test pipes were fabricated by cutting ASTM A-106 carbon steel pipe of 168.3 mm diameter into lengths of 1520 mm [6]. In Alexander and Ochoa's work of combined load effects on CRS, full scale test specimens as large as 4570 mm and 219 mm in length and diameter respectively were manufactured from industrial grade API carbon steel pipes [7]. Despite the advantages, full scale tests incur longer lead times in materials

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http://dx.doi.org/10.1016/j.compstruct.2015.07.066
0263-8223/

preparation, experimental setup and high cost of resources. Scaling laws are often applied to develop prototypes that can capture the mechanical behaviour of a full-scale model at a fraction of the cost and time.

In the current paper, a scaled down version of the experimental testing was used to captures the behaviour of corroded steel risers repaired with different types of FRPC subjected to bending loads. The measured data were used for the characterisation and optimisation of various CRS subjected to combined loadings [9,10]. Scaling laws based on the size ratio between the numerical models and experimental setups of steel pipe were applied. In the scenario where there exist material variation between the numerical model and experimental setup, scaling calculations were done based on the elastic properties of the materials.

2. Materials

2.1. Steel pipe

For the scaled experimental tests, mild steel pipe (modulus = 180 GPa, $v = 0.3$) were selected due to its availability at a significantly lower cost. Mild steel pipes produced from the same batch are taken to avoid inconsistency in material properties. Four dogbone specimens were fabricated and tensile tests were conducted in accordance to the ASTM E8, Standard Test Methods for Tension Testing of Metallic Materials [11]. The specimens were loaded at a rate of 1 mm/min at ambient temperature. The measured true stress–strain response, shown in Fig. 1, was used as an input for the FE model of mild steel pipe.

Within the full model simulation, the material input for the steel riser grade API 5L X60 was selected from a range of steel pipes widely used in the oil and gas industry. The stress–strain relationship was defined using Ramberg–Osgood material model, Eq. (1), as this model was found capable of representing the relationship accurately [12].

$$E\varepsilon = \sigma + \alpha\left(\frac{|\sigma|}{\sigma_y}\right)^{n-1} \tag{1}$$

where E = Young's modulus, ε = strain, σ = stress, α = yield offset factor, n = hardening exponent and σ_y = yield stress of the steel pipe. The model parameters, shown in Table 1, were extracted from Ruggieri and Dotta [13] where crack growth in a high pressure pipeline was numerically modelled.

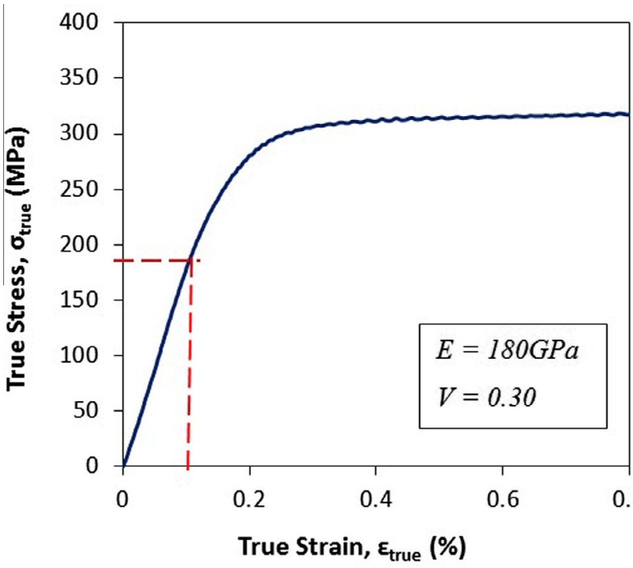

Fig. 1. True stress vs. true strain curve of mild steel pipe.

Table 1
Mechanical properties of API 5L X60 steel.

Parameter	Value
Young's modulus, E [GPa]	210
Poisson's ratio, v	0.3
Yield stress, σ_y [MPa]	483
Ramberg–Osgood's model yield offset, α	1
Hardening exponent in Ramberg–Osgood's model, n	12

2.2. FRPC prepreg

In industrial applications of onshore composite repair, prepregs are widely used as a wrapping system on corroded pipelines. The selected FRPC material for the FE simulation was pre-impregnated composite AS4/3501-6 unidirectional carbon fibre/epoxy system. The properties of the AS4/3501-6 prepreg, shown in Table 2, are identical to those used in the benchmark analysis of the first world-wide failure exercise (WWFE) [14]. For the scaled experimental tests, a Panex35/MTM57 unidirectional carbon fibre/epoxy prepreg system was used. The materials properties, shown in Table 2, were obtained from Coutts-Smith et al. in their work of exploring the bend–twist coupling and structural response of thin laminated beams [15].

A summary of the materials used in both experimental tests and FE simulations is shown in Table 3. The FE simulation using the same materials as the experimental tests (i.e. mild steel and Panex35/MTM57 carbon/epoxy) is conducted to demonstrate the accuracy of the FE model on a case specific basis.

3. Design conditions

The design load (DL) for the bending of the riser must be determined in order to calculate the minimum thickness of the composite repair required in the modelling of the CRS. The technique used here, known as the double-elastic slope method was developed by Alexander [16] based on several industrial design codes and standards similar to Section 6–153 of ASME Boiler and Pressure Vessel Code, Section VIII, Division 2 [17]. The method required the load vs. strain response of uncorroded pipe to be simulated within an FE analysis and its gradient determined, i.e. grad1. The double elastic slope, determined as 0.5 × grad1 can then be plotted through the origin, where its intersection with the load–strain curve gives the corresponding plastic analysis collapse load (PACL). The DL is determined by dividing the PACL with a safety factor which in this case is 2. As shown in Fig. 2, the DL for the bending moment (M_b) is determined as 120 kNm.

The minimum required composite laminate thickness, t_{min}, can be determined through Eq. (2), as described in the

Table 2
Properties of prepreg FRPC.

Fibre type	AS4	Panex35
Matrix	3501-6 Epoxy	MTM57 epoxy
Specification	Prepreg	Prepreg
Manufacturer	Hercules	Umeco
Longitudinal modulus, E_1 [GPa]	126	129
Transverse modulus, E_2 [GPa]	11	7.51
In-plane shear modulus, G_{12} [GPa]	6.6	3.68
Major Poisson's ration, v_{12}	0.28	0.278
Through thickness Poisson's ratio, v_{23}	0.4	0.264
Longitudinal tensile strength, X_T [MPa]	1950	1630
Longitudinal Tensile Failure strain, ε_{1T} [%]	1.38	1.25