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Reliability of corroded thin walled pipes repaired with composite overwrap

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ABSTRACT

Current design codes provide two design methods: allowable stress/strain design and limit state design. Design in the current pipework composite repair codes is based on the allowable design method and only two safety factors are applied to the ultimate strain of the composite layer and to the yield stress of steel. On the other hand, safety factors are applied to each of the load and resistance parameters in the limit state design method. The limit state design method is probabilistic based in which the safety factors are calibrated based on a target reliability index. In this study, an investigation into the reliability of rehabilitated pipelines is conducted. The limit state function is defined based on ASME PCC-2, and reliability analysis is conducted using the AFOSM method. Results show that ASME PCC-2 generally provides adequate safety although the level of safety is not uniform for different percentages of corrosion. Comparing the achieved results and the ISO 2394 target reliability indices, some resistance factors are proposed.

1. Introduction

Transmission pipelines in different industries (oil and gas, water, waste water, etc.) face internal and/or external corrosion after several years of working in corrosive environments. With increased detritions of different pipelines and the ever increasing need for rehabilitation of these pipelines, different methods of repair have been developed. Rehabilitation with fibre reinforced polymers (FRP) is one of the more recent methods of pipeline repair and is well-developed in oil and gas industry. FRP composites have been utilised for the repair of pipelines and piping components in different ways such as cure-in-place polymer liners using pull-in-place and direct inversion methods of installation [1]. Wrapping FRP layers around the defective area of a corroded pipeline is an alternative method of pipeline rehabilitation. FRP overwrap repair systems can decrease the growth rate of the external corrosion as it isolates the external defect from the corrosive environment and is considered as a lifetime repair [2].

In order to assist the engineers with the design of standardised repairs for pipelines and piping systems, two design codes ISO-24817 [3] and ASME-PCC2 [4] were introduced to industries in 2006. These codes categorise the defect types in two different categories as none through-wall and through-wall defects. Both codes are based on the allowable stress design method. In this method, the stress or strain limits are reduced by safety factors. Then, the reduced values are compared with the stress or strain that is resulted from serviceability load combinations.

On the other hand, the Limit State Design (LSD) is a probabilistic method in which safety factors for both load and resistance parameters are applied. In this method, the role of uncertainties in load and resistance related parameters are properly addressed. In order to ensure a certain level of safety in the design process, the load related parameters are increased while those of resistance are decreased. Use of safety factors for both load and resistance, limits the probability of failure to a predefined probability of failure. This means that these safety factors are calibrated in such a way that their use would lead to a uniform level of safety in the design procedure. The probability of failure is often expressed in terms of reliability index, which is the ratio of the mean to the standard deviation of the limit state function. Larger reliability index indicates higher safety level.

Here, a probabilistic method is used to investigate the reliability of pipelines rehabilitated with FRP wraps. The probabilistic models for steel and FRP materials as well as load are derived from the current literature. Two different design equations proposed by the ASME design code are used as a basis for reliability analysis. In one equation, the resistance of the corroded steel pipe is neglected, while in the other, both steel pipe and FRP layers contribute in carrying the internal pressure. The AFOSM method is utilised to calculate the reliability indices. In addition to finding

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the reliability indices of the pipelines designed based on the current design codes, some suggestions are made for the determination of probabilistic resistance factors.

2. Design of overwrap

The two aforementioned design codes use simple equations to design the overwrap repair system. In the case of none through-wall defects, the codes have two different approaches for the design of composite repair. The first approach ignores contribution of the remaining pipe wall thickness in carrying the loads and uses the short-term material properties. Eq. (1) shows the suggested expression for calculating the minimum required thickness of the composite layers in the hoop direction based on these codes.

$$t_{min,c} = \frac{1}{\varepsilon_c}\left(\frac{PD}{2}\frac{1}{E_c} - \frac{F}{\pi D}\frac{\nu}{E_c}\right) \tag{1}$$

When contribution of the remaining pipe wall thickness in carrying the loads is considered, the codes propose Eq. (2) for determination of the minimum required thickness of the composite repair in the hoop direction.

$$t_{min,c} = \frac{PD}{2E_c\varepsilon_c} - s\frac{t_s}{E_c\varepsilon_c} \tag{2}$$

In Eqs. (1) and (2), E_c is the composite module of elasticity, $t_{min,c}$ is the minimum required thickness of composite layer, D is the pipe diameter, P and F are design internal pressure and axial load, respectively. Finally, parameter ε_c is the composite allowable strain. The only difference between the two codes is the definition of s; ASME PCC-2 [5] identifies it as the specific minimum yield stress and ISO 24817 recognises it as the pipe allowable stress. For consistency in this paper ASME PCC-2 code is followed. It is assumed that the internal pressure is the only load that is applied to the pipe. This is not such an uncommon assumption as the usual method of design in the codes is to convert all external forces and internal pressure into a pseudo internal pressure for the design [6,7].

It is also assumed that the design pressure of the repaired pipe is equal to that of the original pipe. Using Eq. (3) which is based on ASME B31.4 [8], this design pressure can be calculated from

$$s_y = \frac{PD}{2t} \tag{3}$$

where s_y is the allowable stress of steel, D is the pipe diameter, P is design pressure and t is the pipe wall thickness.

3. Reliability analysis

3.1. Limit states

As mentioned previously, for the reliability analysis of this study, the LSD method is used. In this method, the concept of a limit state is used to help define failure in the context of structural reliability [9]. A limit state is the boundary between desired and undesired performance of a structure. This boundary is mathematically represented by a performance function. In a general case in which the load and resistance are denoted by L and R, the limit state function, g, is expressed as shown in Eq. (4).

$$g = R - L = 0 \tag{4}$$

Consequently, failure occurs when $R < L$ or $g < 0$, whereas the structure survives when $R > L$ or $g > 0$. In this study, R is the ultimate pressure capacity of the pipe expressed, while L is the internal pressure demand. Eqs. (1) and (2) are used to derive the capacity of the pipeline as a function of the geometric and material properties of steel and FRP composite. Eqs. (5) and (6) show the performance function for cases with and without consideration given to the steel contribution in resisting the internal pressure, respectively.

$$g1 = \frac{2}{D}(E_c\varepsilon_c t_c + st_s)X_M - P = \frac{2}{D}(\sigma_c t_c + st_s)X_M - P \tag{5}$$

$$g2 = \frac{2}{D}(E_c\varepsilon_c t_c)X_M - P = \frac{2}{D}(\sigma_c t_c)X_M - P \tag{6}$$

In Eqs. (5) and (6), σ_c is the ultimate strength of FRP material. All other parameters in Eqs. (5) and (6) were previously defined. The factor X_m is the model error. The model error is the result of simplifications and assumptions made for the derivation of the theoretical model like those proposed by the codes. The model error is defined as shown in Eq. (7).

$$X_M = \frac{\text{Exprimentally measured pressure}}{\text{Theoritical predicted pressure}} \tag{7}$$

3.2. Statistical models

All variables shown in Eqs. (5) and (6) are considered to be random. Statistical models and the model parameters are shown in Table 1. The statistical model for pipe thickness that is shown in Table 1 is for a pipe that is not corroded. In the limit state functions that are shown in Eqs. (5) and (6), the remaining wall thickness of the corroded pipe is used. It is assumed that this thickness follows a similar statistical model to the original pipe wall thickness. The statistical properties of the steel pipe shown in Table 1 are based on API 5LX-65 steel.

The statistical models for FRP composite are taken from an experimental study conducted by Atadero [13], in which an experimental database of more than 780 specimens was used for the statistical analysis. Atadero et al. [11]. investigated the probabilistic model for different number of layers that included one, two and three layers. It was shown that probabilistic models for different number of FRP layers are not the same. The statistical properties of FRP in Table 1 are based on three layers of FRP that is used as the basis for multilayer FRP material. Results presented by

Table 1
Statistical models and relevant parameters used in this study.

Variable		Model parameters	PDF[a]	Reference
Pipe (700 ND)	D	μ=711.2 mm, σ=21.3 mm	Normal	Mustaffa and Van Gelder [10]
	t	μ=25.1 mm, σ=1.3 mm	Normal	
	s	μ=448.2 MPa, σ=31.4 MPa	Normal	
Composite	t_c	α=23.25389, β=2.794 mm	Weibull	Atadero et al. [11]
	$\log(E_c)$	μ=4.377, σ=0.091 mm	Lognormal	
	σ_{uc}	α=8.830, β=1078.949 MPa	Weibull	
Model error	X_M	μ=1.12, σ=0.056	Normal	Avrithi and Ayyub [12]
Internal pressure	P	μ=Nominal, σ=0.10μ	Normal	Mustaffa and Shams [6]

[a] Probability density function.