Investigating the effects of pipe live pressure on the design of composite overwrap repairs

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ABSTRACT:
Pipelines are widely used in oil and gas industry both in offshore and onshore applications. After several years of operation, steel pipelines typically suffer from internal or external metal loss due to erosion and/or corrosion. More than 60% of the oil and gas transmission pipelines around the world are more than 40 years old and in urgent need of rehabilitation in order to re-establish their maximum operating capacity. Different repair methods are available for pipeline rehabilitation; the most recent method exploits the special characteristics of fibre-reinforced polymer (FRP) matrix composite material for rehabilitation. The corroded part of a pipeline is reinforced by wrapping composite material around the pipe. In 2006, two international codes ISO-24817 (International Organization for Standardization 2006) and ASME PCC-2 (The American Society of Mechanical Engineering 2011) were published in order to assist engineers in designing reliable composite overwrap repairs. For the case when the corroded pipe contributes to the load carrying capacity, the codes calculate the repair thickness based on the pipe diameter, remaining wall thickness, pipe and composite material properties, composite allowable strain, design pressure and the live pressure, which is the internal pressure in the pipe at the time of repair application. In this study, a range of design scenarios are modelled using analytical equations and Finite Element method to assess the validity of including live pressure in the design. Results indicate that the repair thickness is independent of the live pressure and hence an appropriate modification is proposed to the existing design equation.

KEYWORDS
ASME PCC-2; Composite; ISO-24817; Pipeline repair

INTRODUCTION

Transmission pipelines in oil and gas industry experience internal and/ or external metal loss due to erosion and/or corrosion due to transportation of the products or owing to operation in a corrosive environment. More than 60 percent of the oil and gas transmission pipelines around the world are more than 40 years old (pipelines international 2009) and in urgent need of rehabilitation in order to re-establish their maximum operating capacity (Freire et al. 2007).

Traditionally most steel pipelines are repaired by removing the corroded part and replacing it with a new pipe or by reinforcing the defected part with an external steel sleeve. Recently, fibre-reinforced polymer (FRP) matrix composite overwrap repair systems have been introduced and accepted as an alternative repair system. It has been integrated into the ASME B31.4 (The American Society of Mechanical Engineering 2009) and B31.8 (The American Society of Mechanical Engineering 2010) pipeline codes and also CSA Z662 (Canadian Standard Association 2007) This method involves reinforcing the corroded part of a pipeline by wrapping FRP around the pipe. Repair with FRP materials presents several advantages over conventional methods. Firstly, the repair is quicker to be performed as the application is easy and straightforward, and the pipeline can continue to operate while the repair is being applied. The risk of fire and explosion due to the welding or cutting is completely eliminated (Duell et al. 2008) and the last but not the least, FRP repair is more economical than the other repair methods. In one comparison, it was found that FRP repair was 24% cheaper than the welded steel sleeve repair and 73% cheaper than replacing the defected pipe section (Koch et al. 2001). FRP overwrap repair system can retard the growth of the external corrosion by isolating the external defect from the corrosive environment so it can be considered as a lifetime repair, while in the case of internal damage an additional way of stopping or de-rating the corrosion or erosion process is required in order to perform a life time repair. In some cases, this can be achieved by the addition of an inhibiting agent in the transporting fluid (Freire et al. 2007). During the past decade it have been proven that FRP is a viable repair system and can be performed adequately under different environmental conditions in industrial project (Duell et al. 2008). The behaviour of a pipe repaired with composite overwrap system has been studied by many researchers in order to understand the effects of different parameters,(Alexander et al. 2008; Alexander & Ochoa 2010; Kessler et al. 2004; Luiz C.M. Meniconi et al. 2002) and different loading conditions(Alexander & Ochoa 2010; Shouman & Taheri 2011).

ASME PCC-2 and ISO 24817 composite repair codes were developed in order to provide the rules for designing a reliable and robust repair. ASME PCC-2 has proposed Equation 1 below for the design of composite repair when the pipe contributes in carrying the load.

$$\varepsilon_c = \frac{PD}{2E_c t_{min}} - s\frac{t_s}{E_c t_{min}} - \frac{P_{live}D}{2(E_c t_{min} + E_s t_s)} \quad (1)$$

Where P_{live} is the internal pressure in the pipe at the time of repair application, E_c and E_s are composite and steel module of elasticity, t_s is remained pipe wall thickness, t_{min} is minimum required thickness of composite layer, D is pipe diameter, s is pipe yield stress, P is design pressure and finally ε_c is the composite allowable strain. Equation 1 indicates that the thickness of composite repair depends on P_{live}. In order to assess the validity of this equation, two different approaches were followed, analytical and FEA modelling

METHODS

Analytical method

Assuming the pipe to be repaired is thin wall (diameter to thickness ratio is more than 20 [ASME B31.4]) and the repair is applied on the defected pipe at the internal pressure (P_{live}), the strain in the damaged pipe (ε_0) due to the internal pressure P_{live}, before applying the repair can be found by Equation 2:

$$\varepsilon_0 = \frac{P_{live}D}{2E_s t_s} \quad (2)$$

After applying the repair the average module of the pipe and composite assembly, (E_{av}) is calculated using Equation 3,

$$E_{av} = \frac{E_c t_{min} + E_s t_s}{(t_{min} + t_s)} \quad (3)$$

The strain in the repaired pipe at the internal pressure (P_{yield}) which causes yielding of the pipe material is given by Equation 4,

$$\varepsilon_{elastic} = \frac{1}{E_{av}} \frac{(p_{yield} - P_{live})D}{2(t_{min} + t_s)} + \varepsilon_0 = \frac{(p_{yield} - P_{live})D}{2(E_c t_{min} + E_s t_s)} + \frac{P_{live} D}{2 E_s t_s} \quad (4)$$

The yield strain of a pipe material is also given by:

$$\varepsilon_{elastic} = \frac{s}{E_s} \quad (5)$$

Equating Equation 4 and 5 and solving for P_{yield}:

$$P_{yield} = \frac{2s(E_c t_{min} + E_s t_s)}{D E_s} - P_{live} \frac{E_c t_{min}}{E_s t_s} \quad (6)$$

For the simplicity of calculations the behaviour of the pipe material is assumed to be elastic perfectly plastic. Therefore as the pressure rises above P_{yield}, the substrate pipe carries no further load and any further load is only carried by the composite. Hence, the strain in the composite due to the pressure beyond P_{yield} is given by:

$$\varepsilon_{plastic} = \frac{(P - P_{yield})D}{2 E_c t_{min}} \quad (7)$$

Finally the total hoop strain in the pipe, $å_s$ is calculated by summing all the strains,

$$\varepsilon_s = \varepsilon_{elastic} + \varepsilon_{plastic} = \frac{s}{E_s} + \frac{(P - P_{yield})D}{2 E_c t_{min}} \quad (8)$$

And the strain in the composite repair laminate is given by Equation 9.

$$\varepsilon_c = \varepsilon_{elastic} + \varepsilon_{plastic} - \varepsilon_0 = \frac{(p_{yield} - P_{live})D}{2(E_c t_{min} + E_s t_s)} + \frac{P_{live} D}{2 E_s t_s} + \frac{(P - P_{yield})D}{2 E_c t_{min}} - \frac{P_{live} D}{2 E_s t_s} \quad (9)$$

Substituting value of P_{yield} from Equation 5 and simplifying, gives:

$$\varepsilon_c = \frac{PD}{2 E_c t_{min}} - s \frac{t_s}{E_c t_{min}} \quad (10)$$

The Equation 10 suggests that the strain in the composite repair laminate is independent of the live pressure acting on the pipe at the time of repair application.

Finite Element Analysis

To further evaluate the validity of the inclusion of P_{live} in the Equation 1 a range of repair scenarios were designed. For each repair scenario the repair thickness was calculated using Equation 1 and 10. The corresponding hoop strain in the pipe and the repair laminate for each design scenario was estimated using the finite element method at the design pressure, then compared to the allowable composite strain. The geometrical and mechanical properties of the pipe to be repaired are given in Table 1. The design pressure for the pipe was calculated to be 27.25 MPa according to ASME B31.4 (The American Society of Mechanical Engineering 2009), considering a design factor of 0.72.

Table 1: Pipe sizes and pipe material

Pipe Material: *API 5L X65*		Pipe size:150 ND	
Modulus, [GPa]	200	OD, [mm]	168.3
Yield, [MPa]	448	Wall, [mm]	7.11

The repair laminate was assumed to be reinforced with a bidirectional carbon fibre stitched fabric with equal number of tows by weight in the weft and warp direction. The matrix was assumed to be epoxy. The fibre volume fraction was assumed to be 40 %. The rule-of-mixture (Daniel & Ishai 1995) was used to calculate the laminate elastic properties, given in Table 2. To calculate the repair thickness the composite allowable strain (ε_c) was limited to 0.3 %, selected as a number in between of two extremes (.25% and .40%) proposed by ASME PCC-2.

Table 2: *Laminate mechanical properties*

Modulus in thickness direction [MPa], E_{TT}	7556
Modulus in hoop direction [MPa], E_{HH}	50602
Modulus in axial direction [MPa], E_{AA}	50602
Poisson's ratio, v_{TH}	0.047
Poisson's ratio, v_{TA}	0.047
Poisson's ratio, v_{AH}	0.037
Shear modulus [MPa], G_{TH}	3174
Shear modulus [MPa], G_{TA}	2209
Shear modulus [MPa], G_{AH}	3174
Allowable repair laminate circumferential strain, ε_c	0.003 mm/mm

Different design scenarios that were considered in this study, are presented in Table 3. The erosion/defect was assumed to be circumferential with a constant depth; the wall thinning was considered in the range of 30% to 80% in steps of 10%. The maximum allowable internal pressure for the corroded pipe was calculated based on ASME B31.4 considering the remained wall thickness of the pipe. In the study, the live pressure was varied from zero to 100% of the maximum allowable live pressure in steps of 25%. The minimum laminate thickness for each repair situation was calculated using Equations 1 and 10 and is given in Table 3.

Table 3: *Different design scenarios*

Defect depth %	Maximum allowable internal pressure in damaged pipe	t_{min} [mm]					
		ASME PCC-2					Equation 10
		P_{live} (Percentage of the maximum allowable internal pressure)					
		0	25	50	75	100	
80	5.45	10.91	10.42	9.95	9.49	9.05	10.91
70	8.18	8.81	8.25	7.73	7.24	6.79	8.81
60	10.90	6.71	6.18	5.70	5.27	4.88	6.71
50	13.63	4.62	4.18	3.81	3.49	3.21	4.62
40	16.35	2.52	2.25	2.03	1.85	1.69	2.52
30	19.08	0.42	0.37	0.33	0.30	0.27	0.42

The pipe was modelled as elastic-perfectly plastic and the yield stress of the pipe was 448 MPa. The material orientation direction for the anisotropic repair laminate is shown in Figure 1 b. The repair laminate through thickness modulus, E_{TT} and the axial modulus, E_{AA} were orientated along the direction '1' and '2' respectively as shown in Figure 1b.

The pipe and the repair laminate were modelled using 2D axisymmetric elements (Abaqus CAX4R; which is a 4-node bilinear axisymmetric quadrilateral, reduced integration and hourglass control element). The FE mesh consisted of 800 and 2400 elements for the pipe and the repair laminate as shown in Figure 1a. The repair laminate thickness for each model is given in Table 3.

a **b**

Figure 1: (a) FEA mesh, (b) Material orientation for repair laminate

The axisymmetric pipe and composite repair laminate was constrained using symmetrical boundary conditions along the wall thickness in the Y-axis near the lower end of the assembly as shown in Figure 2. The pressure load was applied to the internal surface of the tube. The pressure load for all models started from P_{live} and gradually ramped up to the peak pressures.

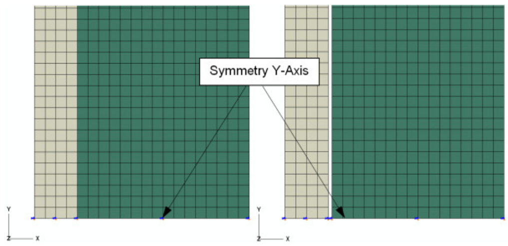

Figure 2: Boundary condition definition for the FEA model

The interface between the pipe and the repair laminate for models with zero P_{live} were modelled using tie constraints i.e. the bond between the pipe and the repair laminate was assumed to be perfect. In the other models, the interface between the pipe and the repair laminate was modelled using standard surface-to-surface contact between the pipe outer surface and the repair inner surface. The tangential (sliding) behaviour of the contact surface was modelled as rough surface i.e. once the contact surface nodes come in contact, the sliding ceases. The normal behaviour of the contact surface was modelled using penalty method and no separation was allowed once the surfaces come in contact. The above specified interaction properties lead to a perfect bonding between the contact surfaces once they come in contact. For the models where the repair was applied at nonzero live pressure, a small gap was modelled between the pipe and the repair laminate as shown in Figure 3, the gap was equal to the expansion of the pipe under P_{live} load. Consequently when the live pressure was applied, the pipe outer diameter and the repair inner diameter come in contact as shown in Figure 3 and a perfect bond was simulated.

RESULTS AND DISCUSSION

The strain in composite repair laminate predicted by FEA at design pressure for the repair designed according to ASME (Equation 1) and that by Equation 10 are shown in Figure 4. Ideally the composite repair thickness calculated according to ASME standard or Equation 10 should be such that the strain in the repair laminate at design pressure does not exceed the allowable composite strain. But, the maximum strain in the repair laminate designed according to Equation 1 (ASME) exceeds the allowable composite strain for many repair situations (Figure 4). At the maximum live pressure, the strain in the composite repair designed using Equation 1 varies from 0.04% to 0.33% for wall thinning of 30% to 80% respectively while for the repair designed using Equation 10; the strain varies from 0.04% to 0.3% for wall thinning of 30% to 80% respectively. At zero live pressure, the repair thickness calculated using ASME and Equation 10 are similar, which bring about similar strains in the composite repair while the corresponding strain varies from 0.13% to 0.30% for wall thinning of 30% to 80% respectively.

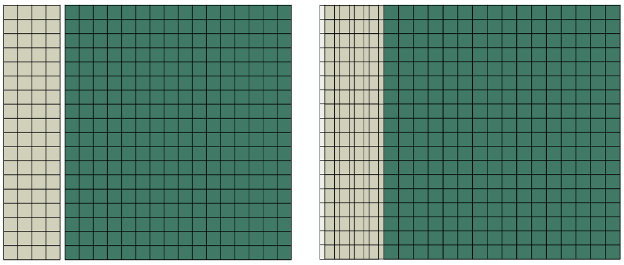

Figure 3: FEA Model (P_{live}>0) showing the gap between pipe and repair laminate

The pipe design pressure is calculated using a design factor of 0.72 [ASME B31.4]. This design factor causes the repaired pipe to yield only if the wall thinning of the eroded pipe is more than 28% (1 – 0.72 = 0.28). As 30% wall thinning is close enough to 28%, the yielding of the pipe is easily influenced by the assumptions made to simplify the problem. The assumptions made to calculate the repair thickness are, the pipe is thin wall, the stress is uniformly distributed through the wall thickness and only hoop stress is considered. Whereas FEA takes account of the radial stress in the pipe, Poisson's ratio effect (contraction in the axial direction due to hoop stress) and the constraints applied by the repair to the contraction of the pipe in the axial direction (because of the bond between the repair and pipe, stiffness of the repair resists the pipe's axial contraction). These factors alter the assumed uniform stress gradient through the pipe and increase the pressure required to yield the repaired pipe, hence lowering the strain in the composite. This is so because, until the pipe yields, majority of the load is carried by the pipe as the elastic modulus of pipe is higher than the composite modulus. Therefore the strain in the composite laminate for 30% pipe wall thinning is not used to derive any conclusions.

As the live pressure increases, the repair thickness designed according to ASME decreases for a given wall thinning (because in Equation 1 subtraction of strain due to P_{live} gives a thinner repair) but the repair thickness generated using Equation 10 stays the same (as it is independent of live pressure). Now comparing the strain in the repair laminates (Figure 4), it is clear that the strain in the 'ASME' laminate is larger than the strain in the 'Equation 10' laminate for nonzero live pressure. Moreover, the strain in the 'ASME' laminate increases with the rise in the live pressure and exceeds the allowable strain (of 0.3%), thus the repair thickness calculated according to ASME standard is smaller than the required thickness. The strain in the laminate based on 'Equation 10' stays the same; this suggests that the strain in the pipe is independent of the live pressure

The deviation of the composite laminate strain (predicted by FEA) from the designed allowable strain in the composite is shown in Figure 5 (zero signifies no deviation). The strain in the repair laminate designed according to ASME standard is -10% (average, ignoring 30% wall thinning) lower than the allowable composite strain at zero live pressure. But as the live pressure increases, the strain in the composite increases and exceeds the allowable composite strain by 22% (average, ignoring 30% wall thinning). The strain in the laminate design according to Equation 10 gives an average deviation of -10% for all the design cases. Hence the strain in the composite repair is not influenced by the live pressure in the tube.

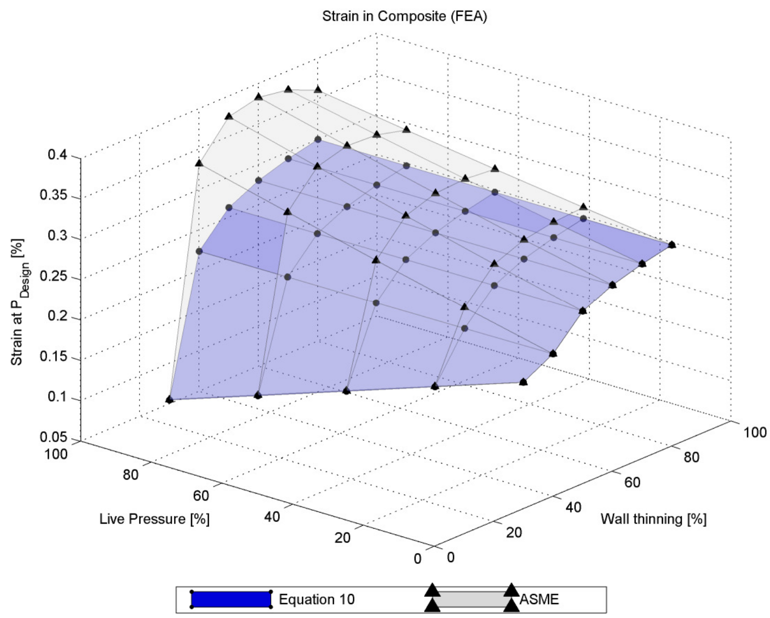

Figure 4: Comparing strain in the Composite at design pressure

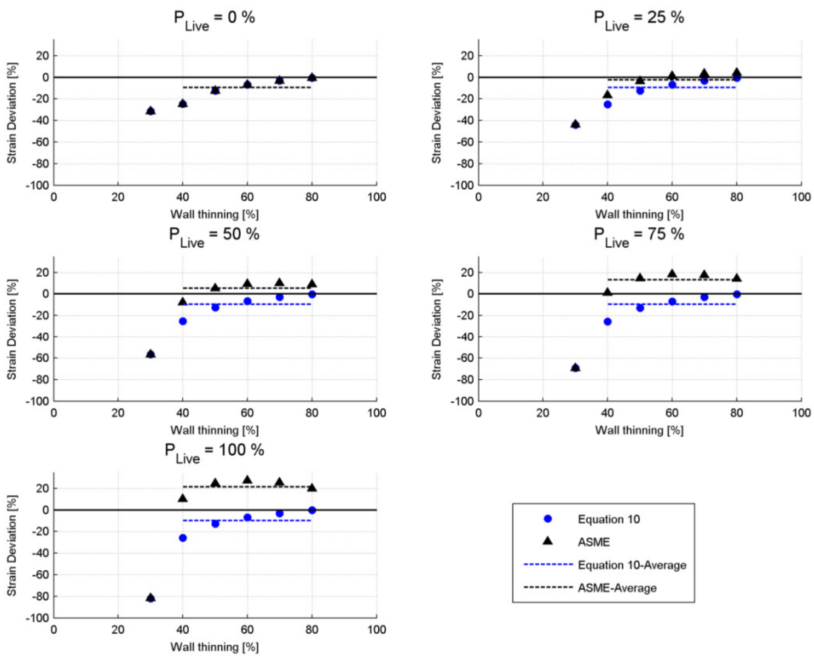

Figure 5: Strain deviation in the composite repair at design pressure

CONCLUSION

The repair laminate thickness calculated using Equation 1 underestimates the repair thickness when the internal pressure is not zero during the repair installation; as such, the hoop strains in the laminate exceed the allowable laminate strain. The live pressure does not influence the hoop strain in the repair laminate at the design pressure as is evident in Figure 5. Equation 10 provides a correct estimate for the composite repair thickness of the pipe when the internal pressure is not zero during the repair installation.

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