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ANALYSIS OF COMPOSITE REPAIR SYSTEMS FOR THIN-WALLED METALLIC PIPELINES WITH LOCALIZED CORROSION

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Abstract. *The present work is concerned with the analysis of composite sleeve reinforcement systems for metallic pipelines with localized corrosion that impair the serviceability. In these systems, a piping or vessel segment is reinforced by wrapping it with concentric coils of composite material. The goal is to propose a simple methodology to estimate the failure pressure of a reinforced specimen with arbitrary localized corrosion damage. Due to the different possible geometries of the corroded region, the exact analysis of this kind of problem can be very complex, in general using an elasto-plastic finite element simulation. The idea is to obtain an approximate exact analytical solution of the problem for any arbitrary geometry of the corroded region and for any arbitrary composite material. For this purpose, initially is presented a solution for thin-walled metallic pipelines with localized corrosion damage without any repair and after it is extended to the case of a corroded pipe reinforced with a composite sleeve. With a simple expression, a reasonable prediction for the failure pressure can be obtained. Experimental burst test pressures obtained in different laboratories were considered to validate the procedure. The results of theoretical predictions are compared with experiments showing a very good agreement for this methodology.*

Keywords: *Polymer based composite repair systems; Corroded metallic pipelines; Elasto-plasticity; Burst pressure estimations*

1. INTRODUCTION

Reinforcement systems composed by composite sleeve are being progressively more used as repair systems for metallic pipelines with localized imperfections or damage that prejudice the serviceability as pointed in Shamsuddoha, et al., 2013 and Chen and Pan, 2013. Composite repair systems are particularly interesting in environments where any repair method using equipment that may produce heat and/or sparkling is forbidden such as in offshore platforms which are hydrocarbon atmospheres. One of the main application is the lifetime extension of corroded pipelines with part-wall metal loss defects in petroleum, petrochemical and natural gas industries, Costa-Mattos, et al., 2009. The damages derived from the corrosion process cause very important economic losses and the classical repair procedures using welding (to cut and replace a corroded segment or to replace a localized damaged section and use a steel patch) besides require stopping the operation while the repair is being performed can be jeopardy by an risk of fire.

The current paper represents a study of thin-walled metallic pipelines with corrosion damage reinforced with polymer based composite repair systems. The study is not focused on the analysis of the different composite systems (see Reis, et al., 2013 and Costa-Mattos, et al. ,2014, for instance) or on their feasibility and suitability as repair systems for corroded pipelines. The aim is to propose a simple methodology to estimate the failure pressure of a reinforced specimen with arbitrary localized corrosion damage only taking into account a few data concerning its geometry, the ultimate stress of the pipe metal and the elastic properties of the composite sleeve. The study is an extension of the methodology presented in Costa-Mattos, et al. (2012) for undamaged pipelines and in da Silva and da Costa Mattos (2013) for corroded pipelines without reinforcement. The analysis of these problems, due to the variety of possible corrosion conditions, may be expensive and time consuming when a finite element simulation is adopted. In da Silva and da Costa Mattos (2013), elasto-plastic constitutive equations presented in Costa-Mattos, et al. (2012) are used to solve analytically the resulting problem, including a factor that takes into account the stress concentration due to loss of material caused by corrosion. This factor is based on expressions found in classical criteria for corroded pipelines (see da Silva and da Costa Mattos, 2013). Generally, the standards for corroded pipelines try to approximate the corroded region through a rectangle or an ellipse with depth corresponding to the greater corrosion depth measured along the pipe axis. The "effective area methods" presented in Stephens and Francini (2000) include the classical ASME B31G criterion, RSTENG 0.85 criterion (also known as modified B31G criterion) and the BG/DNV criterion are used in this method.

The study of the burst pressure of unreinforced corroded pipes is reasonably well established, but still a very active area as can see in Costa Mattos, et al.(2012), Shamsuddoha, et al., 2013Stephens and Francini (2000), Rao, et al. (2005)

,Christopher, et al. (2002), Kaptan and Kisioglu (2007), Cronin and Pick (2002), Adib, et al. (2007), Law and Bowie (2007), Teixeira, et al. (2008), Chiodo and Ruggieri (2009), Zhu and Leis (2012), Lasebikan and Akisanya (2014) and Yan, et al. (2014). Particular expressions proposed to estimate the burst pressure of a corroded pipe without a composite reinforcement system were presented in da Silva and da Costa Mattos (2013). Hydrostatic burst tests are generally recommended for assessing the structural integrity of corroded pipelines. For experimental studies performed in laboratory, regions with reduced wall thickness are artificially created in the specimens, see Fig. 1. The theoretical predictions are compared with results obtained in a series of hydrostatic tests presented in Freire, et al. (2007a), Souza, et al. (2007), Freire, et al. (2007b), Benjamin, et al. (2007) and Benjamin, et al. (2010) showing a very good agreement.

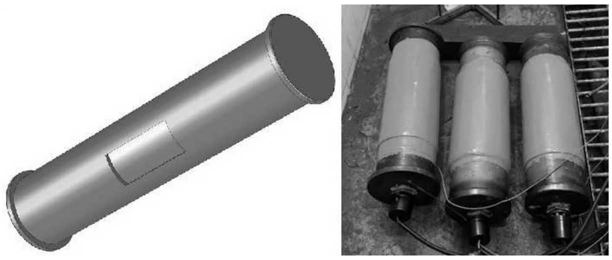

Figure 1. Hydrostatic test specimens with rectangular damage repaired with composite sleeves.

In the sequence, the methodology to estimate the failure pressure of unreinforced corroded pipes is extended to account the effect of the pressure of the composite sleeve on the hoop stress. The basic hypothesis is that the defect is localized and, thus, the stress and strain fields far from the defect are not perturbed by the (localized) plastic deformation. As a consequence, the material behavior is assumed to be elastic far from the corrosion defect and an analytic expression is obtained for the contact pressure P_c . In order to verify the adequacy of such a methodology, the burst pressures obtained in a series of hydrostatic tests of pipes with localized damage reinforced with composite sleeves, Costa Mattos, et al.(2014), Freire, et al. (2007c), Lukács, et al. (2010) and Duell, et al. (2008), are compared with the theoretical predictions. The agreement between model prediction and experiments is also very good. The experimental results have been obtained in different laboratories and the results confirm that it is possible to take advantage of the particular geometry of a thin-walled pipe to obtain a very simple and practical expression to estimate the failure pressure of a reinforced pipe under a localized loss of material (such as a corrosion damage).

2. THIN-WALLED ELASTO-PLASTIC PIPE UNDER INTERNAL PRESSURE

The elasto-plastic constitutive equations considered in this paper have been analyzed in Costa-Mattos, et al. (2009) and da Silva and da Costa Mattos (2013) and only the resulting simplified expressions for the particular case of metallic pipes with localized damage are presented. These equations are adequate to model the monotonic inelastic behaviour of pipes undergoing a quasi-static and isothermal process at room temperature.

It is considered an elasto-plastic cylinder with a localized corrosion damage with internal radius r_i , thickness e submitted to an internal pressure P_i . The internal radius r_i and the thickness e are such that

$$\frac{r_i}{e} > 10 \tag{1}$$

The components of the stress tensor $\underline{\underline{\sigma}}$ in cylindrical coordinates for a thin-walled cylinder are supposed to be reasonably approximated in the framework of membranes theory by the following expression

$$\underline{\underline{\sigma}} = \begin{bmatrix} \sigma_r = 0 & 0 & 0 \\ 0 & \sigma_\theta = \alpha_\theta \sigma & 0 \\ 0 & 0 & \sigma_z = 0 \end{bmatrix} \quad \text{with } \sigma = \frac{P_i r_i}{e} \tag{2}$$

σ_r is the radial stress component, σ_θ the circumferential stress component and σ_z the axial stress component. α_θ is a parameter that takes into account the corrosion damage. It is assumed that the stress component in the axial direction σ_z is negligible in comparison with the hoop stress σ_θ . They are functions of the damaged region geometry and the suggested expressions are presented and discussed in the next sections. The basic empirical hypothesis is that the loss of strength due to corrosion is proportional to the amount of material loss measured axially along the pipe. The term α_z also depends on the boundary conditions and it is more important in short and close-ended pipes under pressure.

Assuming that the stress component in the axial direction σ_z is negligible, it is possible to obtain the following expression relating the pressure P_i with ε_θ^p

$$P_i = \frac{e}{\alpha_\theta r_i}\left[\sigma_y + v_1\left[1 - \exp\left(-v_2\varepsilon_\theta^p\right)\right]\ \right] \text{ if } \left(\frac{P_i r_i}{e}\right) > \sigma_y \tag{3}$$

σ_y is the axial yield stress and v_1, v_2 are positive material constants that characterize the strain hardening induced by plasticity. The yield pressure P_y is obtained assuming $\varepsilon_\theta^p = 0$ in eq. (3)

$$P_y = \frac{e}{\alpha_\theta r_i}\sigma_y \tag{4}$$

The failure pressure $P_{\max}$ is obtained by taking the limit of P_i as $\varepsilon_\theta^p \to \infty$ in eq. (3). Hence,

$$P_{\max} = \frac{e}{\alpha_\theta r_i}(\sigma_y + v_1) \tag{5}$$

$P_{\max}$ is the limit pressure beyond which the hypothesis of quasi-static process is invalid, since the time derivative of the kinetic energy is no longer negligible. From the engineering point of view, such pressure can be taken as the limit pressure (or failure pressure), beyond which it is impossible to make a repair procedure: the rupture process is almost instantaneous after this pressure level is attained (see Fig. 2). Such reasoning is very similar to the one adopted in fracture mechanics in order to define the critical load in a cracked medium. The proof of this fact can be obtained within a thermodynamic framework summarized in Costa Mattos, et al.(2012).

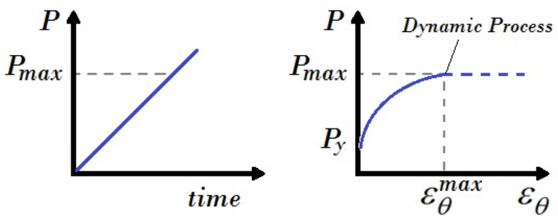

Figure 2. Hydrostatic test with monotonically increasing pressure.

Using the constitutive equations presented in Costa Mattos, et al.(2009) and Costa Mattos, et al.(2012), it is also possible to verify that $(\sigma_y + v_1)$ is exactly the ultimate stress obtained in a tensile test with axial stress component. Therefore, the failure pressure $P_{\max}$ can be related with the ultimate stress σ_{ult} obtained in a tensile test and the following expression is equivalent to (5)

$$P_{\max} = \frac{e}{\alpha_\theta r_i}\sigma_{ult} \tag{6}$$

3. REMAINING STRENGTH CRITERIA FOR CORROSION DEFECTS

Possible expressions for α_θ can be obtained from the criteria presented in da Silva and da Costa Mattos (2013) and Stephens and Francini (2000), generally called *remaining strength criteria for corrosion defects*. All these criteria can be expressed as follows

$$\alpha_\theta \frac{P_i r_i}{e} < \sigma_{flow} \Rightarrow P_{\max} = \frac{e}{\alpha_\theta r_i}\sigma_{flow} \tag{7}$$

where α_θ is a function of geometry and σ_{flow} a maximum admissible tensile strength before failure that varies according to the criterion. Eqs (6) and (7) are not exactly the same since in many criteria σ_{flow} does not coincide with the ultimate stress σ_{ult}. In general, $\sigma_{flow} \leq \sigma_{ult}$. The term is usually called the remaining strength factor. The difference between the many existing methods is the choice of the flow stress and the expression for the remaining strength factor. Many criteria can be found in the literature (ASME B31G Criterion, RSTRENG 0.85 or Modified B31G Criterion, BG/DNV Level 1 Criterion, Chell Limit Load Analysis, Kanninem and Shell Theory Criterion, Sims Pressure Vessel Criteria, Ritchie and Last Criterion and PRC/Batelle PCORRC Plastic Collapse Criterion), but in the present study, only the first three are considered.

$$\text{ASME B31G Criterion:} \begin{cases} \alpha_\theta = \dfrac{1-\dfrac{2}{3}\left(\dfrac{d}{e\sqrt{A_f^{\,2}+1}}\right)}{1-\dfrac{2}{3}\left(\dfrac{d}{e}\right)} \text{ If } A_f \leq 4 \\ \alpha_\theta = \left(\dfrac{e}{e-d}\right) \text{ If } A_f > 4 \\ \sigma_{flow} = 1.1\sigma_y \end{cases} \quad (8)$$

Where (A_f) is a non dimensional factor given by:

$$A_f = 0.893\left(\frac{L}{\sqrt{De}}\right) \quad (9)$$

D is the external diameter, d is the maximum depth of the defect, L the total axial extent of the defect, e the wall thickness of the pipe and σ_y is the yield stress of the pipe (0.5% criterion).

$$\text{RSTRENG 0.85}: \begin{cases} \alpha_\theta = \dfrac{1-0.85\left(\dfrac{d}{e}\right)\left(\dfrac{1}{M_t}\right)}{1-0.85\left(\dfrac{d}{e}\right)} \\ \sigma_{flow} = \sigma_y + 69 \text{ MPa} \end{cases} \quad (10)$$

Where M_t is the bulging factor in the RSTRENG criterion, given by

$$M_t = \sqrt{1+0.6275\left(\frac{L^2}{De}\right)-0.003375\left(\frac{L^2}{De}\right)^2}\ \text{, if } \frac{L^2}{De} \leq 50 \qquad \sqrt{b^2-4ac}$$
$$M_t = 3.3+0.032\left(\frac{L^2}{De}\right)\text{, if } \frac{L^2}{De} > 50 \quad (11)$$

In this paper, based on the elasto-plastic theory (eq. (6)), it is suggest a modification on strength criteria for corrosion defects that will be called, respectively, the ASME B31G* and RSTRENG* criteria, it represents the same expressions for α_θ but to replace the flow stress by the ultimate stress: $\sigma_{flow} = \sigma_{ult}$. As will be seen in the next sections, such a modification gives predictions that are closer to experimental data.

$$\text{BG/DNV Level 1 Criterion}: \begin{cases} \alpha_\theta = \left[\dfrac{1-\left(\dfrac{d}{e}\right)\left(\dfrac{1}{Q}\right)}{1-\left(\dfrac{d}{e}\right)} \right] \\ \sigma_{\max} = \sigma_{ult} \end{cases} \tag{12}$$

Where Q is the bulging factor in BG/DNV Level 1 criterion.

$$Q = \sqrt{1 + 0.31\left(\frac{L^2}{De}\right)} \tag{13}$$

In Freire, et al. (2007a), Souza, et al. (2007), Freire, et al. (2007b), Benjamin, et al. (2007) and Benjamin, et al. (2010) were presented the results of 37 burst tests using specimens with different artificial local metal losses. This is one of the most complete series of experiments found in public literature. Different alloys have been considered: API 5L X80, API 5L X46, API 5L A25, API 5L X42.

ASME B31G and B31G* give the more conservative (and safer) predictions with B31G* being closer to the experimental results in all 37 tests. DNV criterion gives very good predictions, but the burst pressures are higher than the measured ones in a few experiments. RSTRENG* and RSTRENG are less conservative, giving higher estimates of the burst pressures, mainly for particular shapes of the "corroded area" (pipes extensive longitudinal metal losses).

4. THIN-WALLED PIPE UNDER INTERNAL PRESSURE WITH A COMPOSITE SLEEVE

The main ideas presented in the previous section can be extended to the case of a corroded pipe reinforced with a composite sleeve. The basic hypothesis is that the defect is localized and, thus, the stress and strain fields far from the defect are not perturbed by the (localised) plastic deformation. As a consequence, the material behaviour is assumed to be elastic far from the corrosion defect and the pipe-composite sleeve system can be modelled as two concentric thin-walled elastic cylinders submitted to an internal pressure P_i. The pipe has an inner radius r_i and external radius r_o. The sleeve has an inner radius r_o and external radius r_e (Fig. 3). Both metallic pipe and composite sleeve are thin-walled structures: $e = (r_o - r_i) < (r_i / 10)$ and $(r_e - r_o) < (r_o / 10)$ and the expressions for the stress, strain and radial displacement are simple. One important issue is that, in this case, the variation of the wall thickness due to the pressure can be neglected and, thus, the radial displacement u_r can be considered a constant value.

Figure 3: Pipe with metal loss under pressure with a composite reinforcement sleeve.

Assuming that the radial displacement of the contact surface is the same for both cylinders, and neglecting ovalization, it is possible to obtain analytical expressions for the stress, strain and displacement fields. Therefore, the contact pressure P_c between the pipe and the sleeve can be approximated using the following relations

$$[u_r]_{pipe} = [u_r]_{sleeve} \Rightarrow \tag{14}$$

$$r_i[\varepsilon_\theta]_{pipe} = r_o[\varepsilon_\theta]_{sleeve} \Rightarrow \tag{15}$$

$$r_i \frac{[\sigma_\theta]_{pipe}}{E_{pipe}} = r_o \frac{[\sigma_\theta]_{sleeve}}{E_{sleeve}} \Rightarrow \tag{16}$$

$$\frac{r_i}{E_{pipe}}\left(\frac{P_i r_i - P_c r_o}{r_o - r_i}\right) = \frac{r_o}{E_{sleeve}}\left(\frac{P_c r_o}{r_e - r_o}\right) \Rightarrow \tag{17}$$

$$P_c = \left(\frac{r_o^2 E_{pipe}(r_o - r_i)}{r_i^2 E_{sleeve}(r_e - r_o)} + \frac{r_o}{r_i}\right)^{-1} P_i = \eta P_i \tag{18}$$

where $[u_r]_{pipe}$, $[\varepsilon_\theta]_{pipe}$, $[\sigma_\theta]_{pipe}$ are the pipe´s radial displacement, circumferential strain and circumferential stress, respectively. $[u_r]_{sleeve}$, $[\varepsilon_\theta]_{sleeve}$, $[\sigma_\theta]_{sleeve}$ are the sleeve´s radial displacement, circumferential strain and circumferential stress, respectively. E_{pipe} is the elasticity modulus of the pipe and E_{sleeve} the elasticity modulus of the sleeve in the circumferential direction.

Once the contact pressure P_c is determined, the maximum admissible pressure P_i (failure pressure) due to the localised corrosion defect can be approximated by one of the many effective area methods (see section 3)

$$\alpha_\theta\left(\frac{P_i r_i - P_c r_o}{r_o - r_i}\right) < \sigma_{flow} \tag{19}$$

The main difference between the previous equation and the criteria used for the failure analysis using the effective area methods (eq. (7)) is the additional term ($P_c r_o$) that accounts for the contact pressure P_c due to the composite sleeve. Combining eqs. (18) and (19) it is possible to obtain the theoretical failure pressure $P_{\max}^{th}$

$$\alpha_\theta\left(\frac{P_i r_i - \eta P_i r_o}{r_o - r_i}\right) < \sigma_{flow} \Rightarrow \alpha_\theta P_f^{th}\left(\frac{r_i - \eta r_o}{r_o - r_i}\right) = \sigma_{flow} \Rightarrow P_{\max}^{th} = \frac{\sigma_{flow}(r_o - r_i)}{\alpha_\theta(r_i - \eta r_o)} \tag{20}$$

In Table 1 the data are presented whit 17 burst tests with different artificial local metal losses found in Freire, et al. (2007c) [1], Lukács, et al. (2010) [2], Duell, et al. (2008) [3] and Costa Mattos, et al. (2014) [4]. The use of different tests performed by different groups in different places aims to assure that the predictions are reliable and to eliminate the possibility of manipulation of results. Different pipe materials and very different composites have been used in these tests (glass fibre reinforced polyurethane and epoxy composites), but the only necessary property of the composite is the elasticity modulus in the circumferential direction. Tables 1 and 2 summarize the main data and Fig. 4 show the comparison between predicted and experimental failure pressures using the different criteria (ASME B31G*, RSTRENG 0.85*, BG/DNV).

Table 1: Burst tests data.

Test	Ref(1)	Pipe						Composite		$P_{\max}^{exp}$ (MPa)
		E_{pipe} (GPa)	σ_{ult} (MPa)	D (mm)	e_{pipe} (mm)	d (mm)	L (mm)	E_{sleeve} (MPa)	e_{sleeve} (mm)	
1	[1]	210000	608	508	14.3	10.01	500	20000	25	27.9
2	[1]	210000	604	508	14.3	10.01	500	20000	25	26.7
3	[1]	210000	600	508	14.3	10.01	500	20000	25	23.6
4	[1]	210000	600	508	14.3	10.01	500	20000	25	23.5
5	[1]	210000	563	508	14.3	10.01	500	27000	25	19.2
6	[1]	210000	563	508	14.3	10.01	500	27000	25	20.2
7	[1]	210000	616	508	14.3	10.01	500	27000	25	22.8
8	[1]	210000	621	508	14.3	10.01	500	27000	25	23.2
9	[1]	210000	605	508	14.3	10.01	500	28000	25	23.5
10	[1]	210000	583	508	14.3	10.01	500	28000	25	23.4
11	[1]	210000	621	508	14.3	10.01	500	8000	25	19.9
12	[2]	205000	603	323.9	7.10	3.00	100	47600	3.12	27.32
13	[3]	207000	474	168.3	7.11	3.56	152.4	49000	3.10	43.8
14	[3]	207000	474	168.3	7.11	3.56	152.4	49000	3.10	43.1
15	[4]	210000	613	476.4	9.53	6.70	450	21700	21.42	14
16	[4]	210000	613	476.4	9.53	6.70	450	21700	21.42	14.2
17	[4]	210000	613	476.4	9.53	6.70	450	21700	21.42	14.2

(1) Referenced in accordance on the paragraph above.

Table 2. Burst pressure predictions (MPa).

Test	$P_{\max}^{\exp}$	ASME B31G*	RSTRENG*	DNV
1	27.90	12.59	19.65	15.73
2	26.70	12.51	19.52	15.63
3	23.60	12.43	19.40	15.52
4	23.50	12.43	19.40	15.52
5	19.20	12.21	19.06	15.26
6	20.20	12.21	19.06	15.26
7	22.80	13.36	20.86	16.70
8	23.20	13.47	21.03	16.83
9	23.50	13.21	20.62	16.50
10	23.40	12.73	19.87	15.90
11	19.90	11.81	18.44	14.76
12	27.32	25.08	23.85	24.08
13	43.80	23.91	31.22	29.22
14	43.10	23.91	31.22	29.22
15	14.00	9.28	14.37	11.30
16	14.20	9.28	14.37	11.30
17	14.60	9.28	14.37	11.30

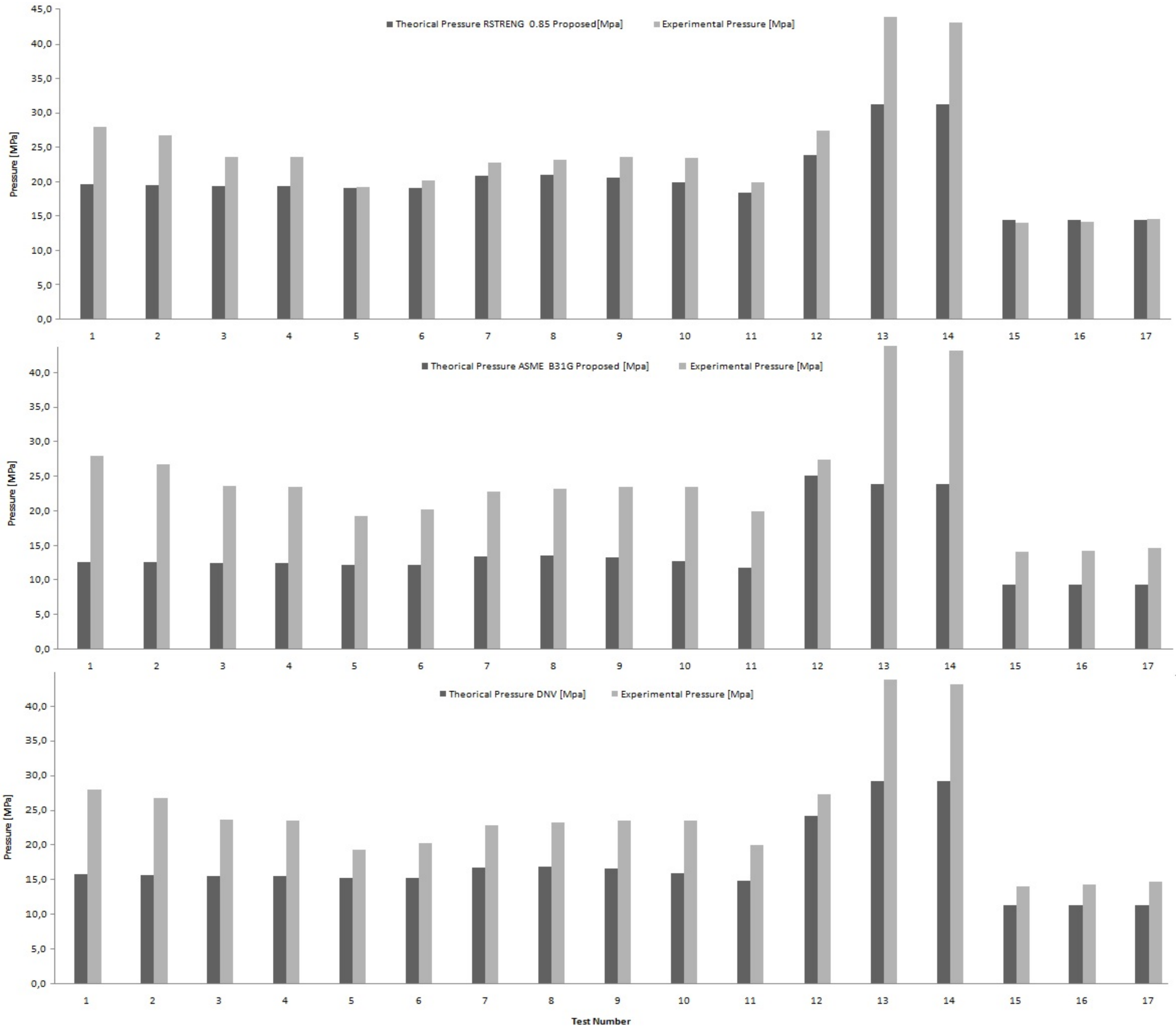

Figure 4: Comparison between predicted and experimental pressures for different criteria (in MPa).

Figure 5 presents the ratio between the predicted burst pressures and the experimental burst pressures $(P_{\max}^{th} / P_{\max}^{\exp})$ using the criteria RSTRENG*, B31G* and DNV. Fig 4 shows the comparison between these pressures (in MPa). B31G* gives the more conservative predictions. DNV gives good predictions, and RSTRENG*, that tends to be less conservative (and accurate) in the prediction of the burst pressures of corroded pipes without a composite repair, has the best performance, in these cases.

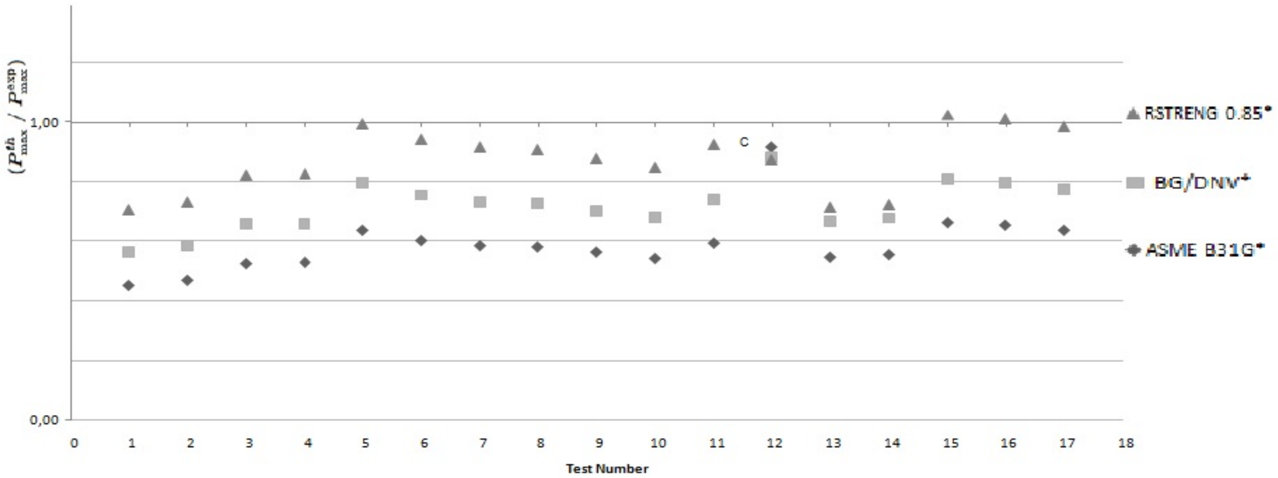

Figure 5: Ratio between the predicted burst pressures and the experimental burst pressures.

This apparent paradox was explained in Lopes Junior (2015). The approximate procedure (eqs. (14) to (18)), that assumes elastic behaviour of both pipe and composite and uses membrane theory, tends to overestimate the contact pressure and, consequently, to underestimate the hoop stress. Therefore, the use of a less conservative criterion (RSTRENG*, that gives higher values for the parameter α_θ) in eq. (20) may compensate this fact giving better predictions of the burst pressure.

As pointed in da Costa Mattos, et al. (2014) and da Costa Mattos, et al. (2012), more accurate predictions can be obtained if the following issues are taken into account in the analysis: (i) the effect of the specimen extremities (the stress component in the axial direction is not neglected); (ii) the variation of the thickness of the composite glove(the stress component in the radial direction is not neglected) and; (iii)the perturbation caused by the localized plastic deformation in eq. (18). However, the resulting expressions are complex, require additional experimental parameters, and, due to the scatter of experimental results, not necessarily give a more reliable prediction.

5. CONCLUSIONS

The present paper proposes a simple methodology to obtain a preliminary, but satisfactory, estimate of the failure pressure of a thin-walled metallic pipe line with arbitrary localized corrosion damage reinforced with polymer based composite repair systems. Such a methodology can also be used to define the necessary composite repair thickness in order to assure a reliable operation of a corroded metallic pipe conveying liquids.

Analysis more accurate in this kind of problem requires numerical simulations and/or specific hydrostatic testing, due to the different geometries of the corroded region. The approximate analytical solution of the problem proposed here is adequate for a variety of geometries of the corroded region. With a simple algebraic expression, a reasonable estimate for the failure pressure of a corroded thin-walled pipe reinforced with an arbitrary composite glove can be obtained. This estimate only requires the knowledge of the elastic modulus of the composite in the circumferential direction and of the ultimate stress of the pipe material obtained in a tensile test, besides a few information about the geometry (composite thickness, pipe inner diameter and wall thickness and the average geometry of the flaw).

Experimental results found in papers from different laboratories were analysed to consider that the proposed method can be validated (37 hydrostatic burst tests with different types of localized metal losses without reinforcement composite system and 17 tests with different types of localized metal losses and different kinds of composites sleeves). Experiments performed by different research groups were chosen on purpose to eliminate the possibility of manipulation of the results.

The correlation between model prediction and experimental result is very good in all cases. These preliminary results show that the proposed methodology can be adopted as a preliminary tool in the design and/or analysis of composite repair systems for corroded pipelines.

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