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REPAIR OF TROUGH-THICKNESS CORROSION DAMAGE IN PIPELINES WITH METALLIC PATCHES BONDED WITH ADHESIVES

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Abstract. *The present paper is concerned with the repair of through-wall corrosion damage in metallic pipes using a bonded metallic patch. The focus is on the analysis of the influence of the thickness of the patch on the effectiveness of the repair. The goal is to assure that the pipe won't leak once the repair is completed. The main motivation for the study presented in this paper is the corrosion damage in produced water pipelines used in offshore oil exploitation. Since offshore platforms are hydrocarbon atmospheres, any repair method using equipment that may produce heat and/or sparkling is forbidden. Usually a composite sleeve is used together with a metallic patch. The main motivation for this study is to show that only a bonded metallic patch can be sufficient to avoid leaking (no composite sleeve is necessary), but the effectiveness of the repair is strongly dependent on the thickness. Normally, most studies are concerned with the bonded area, but experimental results show that the failure pressure using patches with the same area but with different thicknesses can be very different. Burst tests have been performed on API 5L grB steel hydrostatic specimens with a 25,4 mm hole repaired with 100 mm X 100 mm patches. Depending on the thickness, the failure pressure can vary from 70 to 270 bar.*

Keywords: *metallic patches, pipeline repair, adhesives*

1. INTRODUCTION

Many studies concerning composite repair systems performed in the last years (da Costa Mattos et al., 2009), (da Costa Mattos et al., 2012), (da Costa Mattos et al., 2013), (da Costa Mattos et al., 2014), (da Costa Mattos et al., 2016), (da Costa Mattos et al., 2017). The standards ISO 24817 and ASME PCC-2, show the method to repair a trough-wall damage is using a composite sleeve, but the standards don´t specify anything regarding the use of a bonded metallic patch in the repair of trough-wall corrosion damage. Since it is not forbidden by the standard, the repairs are performed using the composite sleeve over a bonded metallic patch to improve the resistance. The utilization of the composite sleeve is important when there is metal loss due to corrosion in large areas in the tube, however, when the damage is a localized trough-wall metal loss, the use of a metallic patch is enough to avoid leaking and to assure the pipeline integrity. The present study is concerned with the influence of the patch thickness on the repair effectiveness. Very thin patches are more flexible than thicker ones. The debonding mode changes due to flexure for metallic patches with the same shape and area but with different thicknesses. The thicker the metallic patch is, more pressure the repair can support, until a given limit beyond which the patch behaves almost as a rigid element and the thickness no longer influences the repair strength.

2. MATERIALS AND METHODS

A steel tube made of API 5L grB, with a hole in the lateral, centered in the tube, was used for the test. Table 1 shows the parameters for the tube used:

Table 1. Parameters of the pipe.

External diameter	152.4 mm
Thickness of the pipe	7.11 mm
Diameter of the hole	25.4 mm

The patches used in the present study have a rectangular shape of 100 mm x 100 mm and the same curvature of the pipe. The material of the patch is ASTM A36 steel. In order to achieve the roughness levels required for the use of the selected adhesive (from 25 to 75 µm), the surface preparation was carried out with a recyclable abrasive blasting media to achieve a white metal appearance and to remove any oxide layer. Figures 1 and 2 shows the metallic patches.

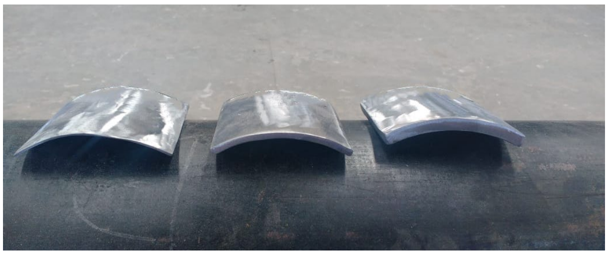

Figure 1. Metallic Patches.

Figure 2. Surface treated.

The adhesive 1 used was a two-component system consisting of a base and solidifier, conceived for leak repair on tanks and pipes as well as for other emergency applications. The product is based on an adhesive of epoxy matrix and it is partly cured after 6 – 8 hours and it is fully cured after 3 – 5 days at 25ºC or 20 -24 hours at 50 °C. Further technical data is presented in table 2.

Table 2: Technical data – Adhesive 1

flexural strength	120 MPa
Tensile strength	55 MPa
modulus of elasticity	9,5 GPa

The Adhesive 2 is based on a silicon steel alloy blended within high molecular weight polymers and oligomers and it is partly cured after 35 minutes at 25ºC and it is fully cured after 1 hour at this temperature. Further technical data is presented in table 3.

Table 3: Technical data – Adhesive 2

flexural strength	59 MPa
tensile shear on steel	17 MPa
compressive strength	56 MPa
heat distortion temperature (HDT)	51ºC

The patches were bonded to the pipe with the adhesive with an average thickness of 4 millimeters. Figure 3 shows the process of applying the metallic patch on the pipe surface.

Figure 3. Processing of bonded metallic patches

Hydrostatic tests were performed to calculate the failure pressure.

3. RESULTS AND DISCUSSION

Table 4 and 5 show the failure pressures obtained for both adhesives

Table 4. Failure Pressure. Adhesive 1.

	Thickness (mm)				
Metallic Patches	1	2	3	6	9,5
Test	Failure Pressure (MPa)	Failure Pressure (MPa)	Failure Pressure (MPa)	Failure Pressure (MPa)	Failure Pressure (MPa)
1	7.9	16.4	16.3	27.5	27
2	8.1	11.3	23.7	21	23.9
3		11.6	18.7	28.7	23.3
4				23.5	
Average	8.0	13.1	19.6	25.2	24.7

Table 5. Failure pressure. Adhesive 2

Metallic Patches	Thickness (mm)	Failure Pressure (MPa)
Patches 1	2	6.6
Patches 2	6	10.5
Patches 3	9.5	11.5

Two models are proposed in this next section. One model is based on the Linear Elastic Fracture Mechanics and follows the ideas and simplifying hypothesis used both in ISO 24817 and ASME PCC-2 standards. The second one is an empirical equation that relates the failure pressure to the patch thickness. The tests depicted in Table 4 and 5 show that the thicker the metal patch is, the more pressure it can support, until a given limit.

The main idea of both ISO and ASME standards to obtain a lower limit of the failure pressure is to simplify the analysis by assuming that the curvature of the pipe wall is small and does not influence the critical energy release rate. With this assumption the problem is simplified to that of a pressurized circular delamination between a substrate (steel) and the repair (patch), see Figure 4. Furthermore the substrate is assumed to be rigid.

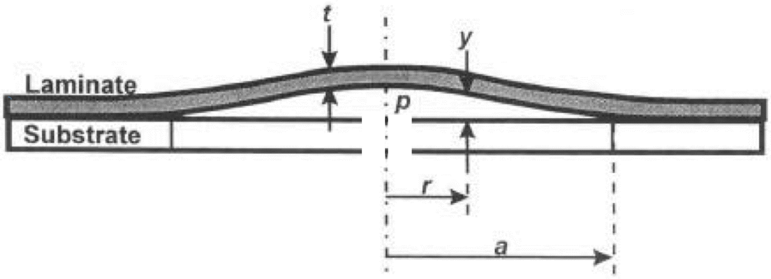

Figure 4. Delamination of the patch

The energy criterion for fracture is primarily an extension of Griffith's criterion for quasi-static crack growth or propagation and represents a conversation of work done, W_d, by external forces plus internal stored elastic energy, U, into surface free energy, γ. γ includes all energy losses around the crack tip and can be described as the energy required to increase the crack area A, by an amount ∂A. This criterion of fracture is given by

$$\gamma = \frac{\partial (W_d - U)}{\partial A} \tag{1}$$

In Equation (1), the difference in external work and internal energy, for structures, bonded ones included, exhibiting bulk linear elastic behavior away from the vicinity of the crack tip, can either be expressed in terms of the applied pressure, p, and the resulting volume, V;

$$W_d - U = pV - \frac{1}{2}pV = \frac{1}{2}pV \tag{2}$$

Inserting equation (2) into equation (1) gives;

$$\gamma = \frac{1}{2}p\frac{\partial V}{\partial A} \tag{3}$$

Equation (3) implies that the critical energy release rate is a function of the pressure and the rate of change in volume with respect to crack area. The failure criterion is to assume a critical energy release rate γ_{CR} . The crack propagation is stable provided $\gamma < \gamma_{CR}$. If a monotonically increasing pressure is applied, a brutal (unstable) propagation will occur when $\gamma = \gamma_{CR}$. The so-called critical pressure P_f is the pressure associated with the critical energy rate. Similarly as in ASME PCC-2 and ISO 24817, the following expression can be obtained (the analysis is not presented here due to the limited space)

$$P_f = \sqrt{\frac{0.001\gamma_{LCL}}{\frac{(1-\nu^2)}{E}\left\{\frac{3}{512t_i^3}d^4 + \frac{1}{\pi}d\right\} + \frac{3}{64Gt_i}d^2}} \tag{4}$$

E is the tensile modulus of the metallic patch, expressed in megapascals;
G is the shear modulus of the metallic patch, expressed in megapascals;
P_f is the failure pressure, expressed in megapascals;
ν is the Poisson's ratio of the metallic patch
D is the diameter of the defect, expressed in millimeters;
t_i is the thickness of the metallic patch, expressed in millimeters;
γ_{LCL} is the 95 % lower confidence limit of energy release rate, expressed in joules per square meter.

G is calculated with equation 5.

$$G = \frac{E}{2(1+\nu)} \tag{5}$$

The $A(t_i)$ is calculated using Formula (6).

$$A(t_i) = \sqrt{\frac{0.001}{\frac{(1-\nu^2)}{E}\left\{\frac{3}{512t_i^3}d^4+\frac{1}{\pi}d\right\}+\frac{3}{64Gt_i}d^2}} \quad (6)$$

The mean energy release rate, Υmean, is calculated using Formula (7).

$$\gamma_{mean} = \left(\frac{\sum_{i=1}^{n} A(t_i)p_i}{\sum_{i=1}^{n} A(t_i)^2}\right)^2 \quad (7)$$

The lower confidence limit of the energy release rate, γ_{LCL}, is calculated using Formula (8):

$$\gamma_{LCL} = \left[\frac{\sum_{i=1}^{n} A(t_i)p_i}{\sum_{i=1}^{n} A(t_i)^2} - t_\nu\sigma\sqrt{\frac{1}{\sum_{i=1}^{n} A(t_i)^2}}\right]^2 \quad (8)$$

where σ is the variance of measurement of pressure and is given by Formula (9):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(p_i - A(t_i)\sqrt{\gamma_{mean}})^2}{(n-2)}} \quad (9)$$

and where t_ν is the Student's t value and is based on a two-sided 0.025 level of significance, i.e. 95 % lower confidence limit. Values of t_ν are given as a function of number of variables, n. Table 6 and 7 summarize the determination of γ_{LCL}

Table 6: γ_{LCL} calculation

$A(t_i)$	d (mm)	t_i (mm)	p_i (Mpa)	$A(t_i)^2$	$A(t_i)p_i$	sup σ	γ_i
0.295	25.4	1	7.9	0.087	2.327	26.625	719.4
0.295	25.4	1	8.1	0.087	2.386	28.729	756.3
0.786	25.4	2	16.4	0.617	12.883	82.667	435.8
0.786	25.4	2	11.3	0.617	8.877	15.937	206.9
0.786	25.4	2	11.6	0.617	9.112	18.422	218.1
1.314	25.4	3	16.3	1.728	21.424	16.587	153.8
1.314	25.4	3	23.7	1.728	31.151	131.623	325.1
1.314	25.4	3	18.7	1.728	24.579	41.896	202.4
2.551	25.4	6	27.5	6.506	70.144	14.225	116.2
2.551	25.4	6	21	6.506	53.564	7.444	67.78
2.551	25.4	6	28.7	6.506	73.205	24.716	126.6
2.551	25.4	6	23.5	6.506	59.941	0.052	84.88
3.313	25.4	9.5	27	10.973	89.439	14.562	66.44
3.313	25.4	9.5	23.9	10.973	79.170	47.831	52.06
3.313	25.4	9.5	23.3	10.973	77.183	56.490	49.47

Table 7: Results

γ_{mean} =	86.54
σ =	10.274
γ_{LCL} =	32.649

An even more simplified expression can be proposed for the failure pressure P_f.

$$P_f = a(1 - exp(-bt)) \tag{10}$$

Where a and b are positive constants. From eq. (10) it can be verified that a is the limit pressure a patch with this area can support

$$\lim_{t\to\infty} P_f = a \tag{11}$$

For the first adhesive, the following values of the parameters are obtained using the average experimental pressure values for each plate thickness: $a = 26.4$ (MPa) and $b = 0.39$. Figure 5 shows the comparison between experiments and both model predictions. In this figure, we will call Model I the prediction obtained using the simplified fracture mechanics analysis and Model II the proposed empirical equation (10).

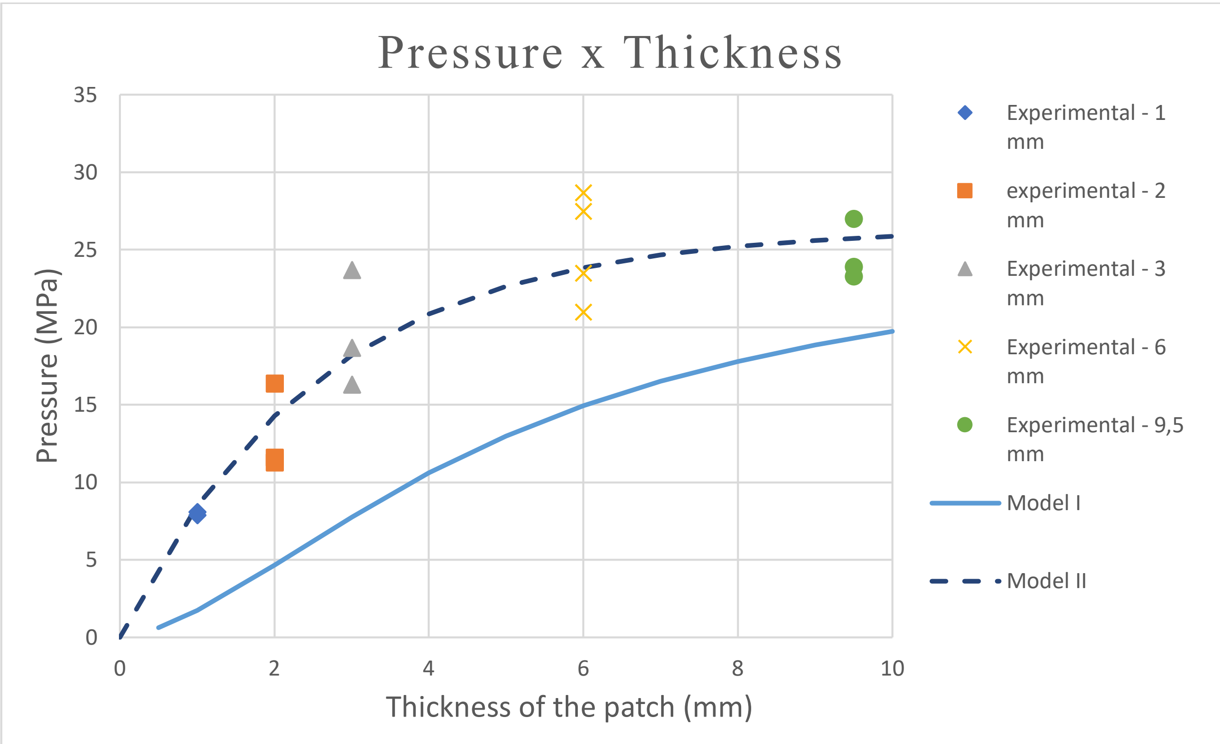

Figure 5: Failure Pressure x Thickness.

As can be seen in Figure 5, Model I can be used as a lower limit for the failure pressure, whereas Model II can be used as an upper limit. To check the adequacy of the empirical model II, a few tests have been performed with adhesive II and the results are presented in Figure 6. In this case, the positive constants are, $a = 11.6$ (MPa) and $b = 0.41$.

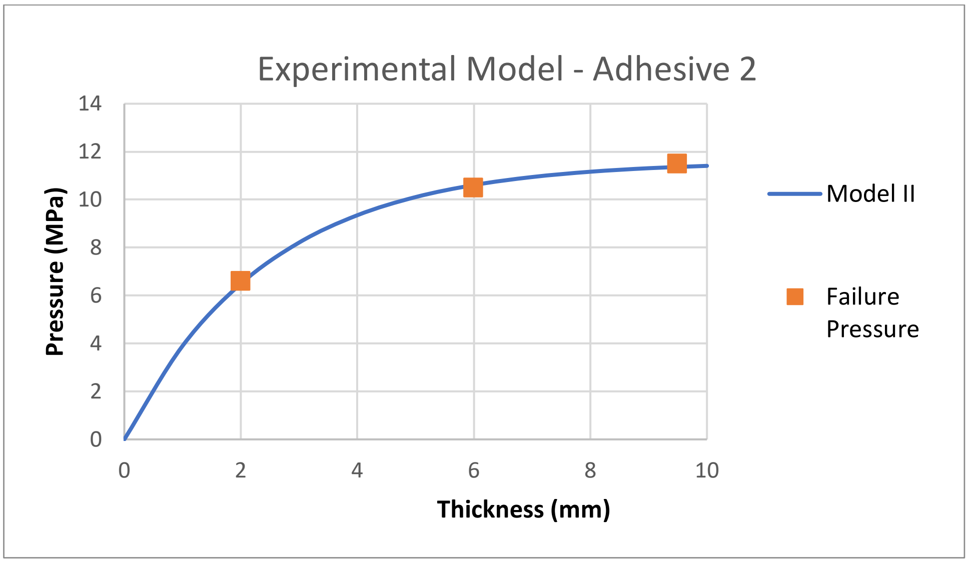

Figure 6: Failure Pressure x Thickness of adhesive 2.

The Figures 7, 8, 9, 10 and 11 show the failure modes for different thicknesses (adhesive, cohesive, mixed mode).

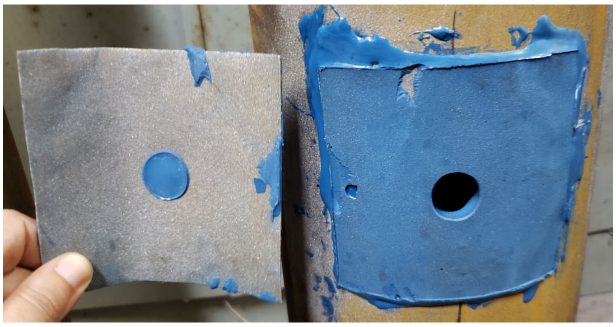

Figure 7: Failure mode, 1 mm thickness.

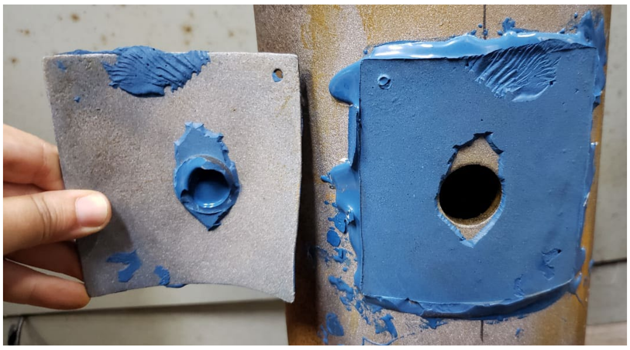

Figure 8: Failure mode, 2 mm thickness.

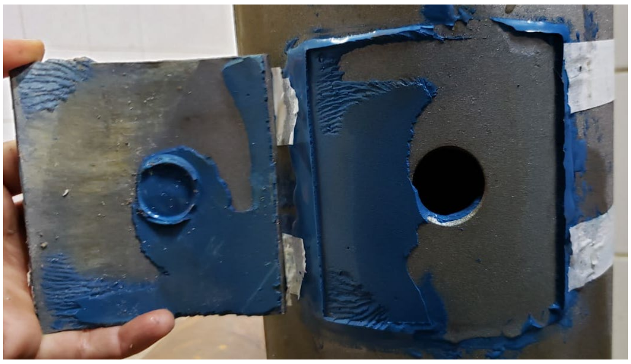

Figure 9: Failure mode, 3 mm thickness.

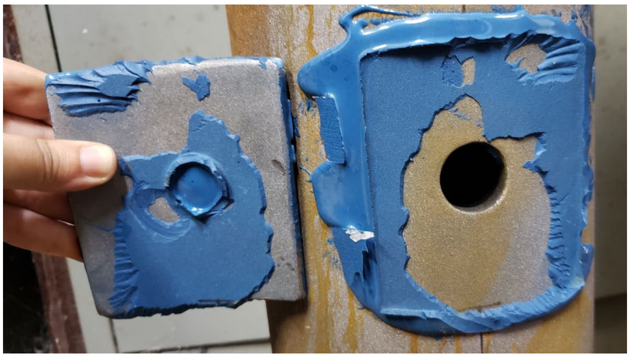

Figure 10: Failure mode, 6 mm thickness.

Figure 11: Failure mode, 9.5 mm thickness.

4. CONCLUSION

The present paper investigates the possibility of using metallic patches in the repair of pipes with localized trough-thickness damage. Besides, it analyzes the influence of the thickness of the patch in the failure pressure. Repairs with thicker patches can support higher pressures until a given limit. The average failure pressure varied from 8.0 MPa to 25.2 MPa with the thickness varying from 1 mm to 9.5 mm.

Beyond a given thickness, the effectiveness of the repair does not change significantly. Both models are good approximations to represent the failure pressure of a patch repair. More tests will be performed to have more precision in the analysis. However, for practical purposes, it seems that a reasonable limit thickness of the metallic patch could be the pipe thickness (in the present case 7.11 mm).

5. REFERENCES

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