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NUMERICAL ANALYSIS OF THE EFFECT OF THE REPAIR OF CORRODED PIPELINE WITH COMPOSITE PATCHES ON THE PREDICTION OF FAILURE PRESSURE

NUMERIČKA ANALIZA UTICAJA REPARACIJE KORODIRANOG CEVOVODA SA KOMPOZITNIM ZAKRPAMA NA PROCENU PRITISKA ZA LOM

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Ključne reči
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- nelinearno
- reparacija
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Abstract

The present paper focuses on the numerical prediction of failure pressure for a corroded pipeline before and after repair using composite materials patch. In the first step, the failure pressure of the corroded pipe subjected to internal pressure, has been predicted and validated using nonlinear behaviour. Then, effects of length, width and spacing of corrosion pits on failure pressure were discussed. In the second and last step, the corroded pipe is repaired with two kinds of composite patch, based on synthetic and natural fibres and the effect of reinforcement is observed. The limit of repair under increasing internal pressure is studied. The good results obtained make it possible to decide on the developed numerical model and on its reliability in predicting the failure pressure of corroded tubular structures and principally in optimising the thickness of the biocomposite patch repair.

Izvod

U radu se fokusira na numeričkom predviđanju pritiska pri lomu korodiranog cevovoda pre i posle popravke korišćenjem zakrpe od kompozitnih materijala. U prvom koraku, pritisak pri lomu korodirane cevi, opterećene unutrašnjim pritiskom, je procenjen i proveren analizom nelinearnog ponašanja. Zatim su razmotreni uticaji dužine, širine i razmaka korozionih jama na pritisak loma. U drugom i poslednjem koraku, korodirana cev se reparira sa dve vrste kompozitnih zakrpa, na bazi sintetičkih i prirodnih vlakana, i razmatra se uticaj ojačanja. Razmatra se obim popravke sa povećanjem unutrašnjeg pritiska. Dobijeni su pogodni rezultati, koji doprinose donošenju odluke u izboru razvijenog numeričkog modela i njegove pouzdanosti u predviđanju pritiska loma korodirane cevovodne konstrukcije, a pre svega u optimizaciji debljine reparacione biokompozitne zakrpe.

INTRODUCTION

In the United States alone, there are more than 50 % of gas pipes reaching an age beyond 40 years /1/. The corrosion of pipelines leads to a lot of damage which reduces in general their strength and structural integrity and causes very significant economic losses. The classical repair procedure based essentially on welding (to cut and replace a corroded segment, or to replace a localised damaged section and use a steel patch) requires stopping the operation during the execution, causing pipe ruptures rather than leaks, and impacting on the pressure containing capacity of a pipe for repair. Any unplanned shutdown to repair critical or leaking defects on oil and gas transmission pipes costs millions of dollars, which includes costs of repair and loss of production, among others.

In order to avoid this situation, another repair method can be used to maintain the operation of the pipeline. It consists of the reinforcement by composite sleeve systems. This procedure is being increasingly used for metallic pipelines with localised imperfections or damages that impair serviceability, /2-3/. Such reinforcement is applied in order to extend the lifetime of corroded pipelines with part-wall metal loss defects. This repair is very quick because no welding is required and therefore destruction of the original structure and stress concentration are avoided /4-7/. Also, a corrosion-resistance added to better fatigue properties are also offered, compared to the other methods, /8/.

To be noted is that synthetic composite repair systems are particularly interesting in environments where any repair method using equipment that may produce heat and/or sparks is forbidden (such as hydrocarbon atmospheres on offshore platforms). The synthetic composites have also been chosen due to lightweight, high strength and stiffness, excellent fatigue properties, and good corrosion resistance, /9-10/.

Although products made by different companies and research institutes exhibit widely varying performance, in general, a synthetic composite material repair system includes the following three parts: (i) a high-strength FRP composite wrap/clamp; (ii) a high-performance adhesive; and (iii) a high-compressive infill material.

In this paper, we focus to present a new patch made of biocomposite, where several research studies focus on the replacement of synthetic composite by eco-composites based on natural fibres. This interest is justified because of their widespread availability, lightness, strength, biodegradability, sustainable and renewable nature, in addition to their high specific modulus and low cost, low wear of tooling, skin irritation, and environmental-friendliness, /11/.

Reparation of the corroded pipe using the synthetic composite- or biocomposite patch is considered as reinforcement which permits the continuation of its operation by avoiding the failure of pipe under internal pressure. The composite patch replaces lost thickness by corrosion. The resistance is increased and pipe failure is then avoided. It is important to know that a pipeline with corrosion defects can continue to operate if Maximum Allowable Operating Pressure (MAOP) passes the reliability assessment by determining the failure pressure, /12-14/. Various models as in the American Society of Mechanical Engineers (ASME) B31G standard /15/, the computer code 'modified B31G' /16, 17/, and the DNV-RP-F101 standard /18/, have been used widely for assessing of defects in determining the failure pressure in pipelines. Previously mentioned literature shows that this recommended practice gives conservative results in terms of the estimated failure pressure, /19/.

Finite element analysis (FEA) as a useful tool has been utilised in demonstrating the accurate limit loads of pipelines with or without corrosion defects. The 3D nonlinear finite element analysis can predict the burst pressure and burst failure location of the cylindrical shell, based on the plastic instability failure criterion, /20/. Also, FEA is capable of analysing more complex shapes and situations such as multiple corrosion defects and complicated corrosion defects, /21/. Accordingly, the theoretical development of the finite element method (FEM), numerical simulation is used to examine the local details of the structure, /22/. Bipul et al. /23/, confirmed that the conventional Von-Mises stress-based approach and design equations can reasonably be used for predicting burst pressures in pipelines with corrosion only defects. However, the fracture mechanics approach is required for pipelines with crack-like defects and crack-in-corrosion defects at various crack depths and crack lengths.

The principal aim of this study is to design a composite system to repair a corroded pipe incorporating design requirements, material selection, and installation techniques. The design requirements for this effort were to ensure that the Von Mises stress due to internal pressure remains below the circumferential ultimate true stress of 631 MPa.

To do that, a corroded pipeline with a single corrosion pit is investigated using a nonlinear finite element method, and effects of length, width, and spacing of corrosion pits of the failure pressure are discussed. Some results were compared to the RSTRENG method and previous experimental data. Then the same assessment using FEA was conducted on the corroded pipe, reinforced by a synthetic composite and biocomposite patch. The necessary thickness and number of plies to avoid pipe failure have been determined. The optimisation of repair parameters such as types of reinforcement and fibre orientation are considered within developed FE models.

PROBLEM AND RESOLUTION METHODOLOGY

At an LPG plant in the west of Algeria, after 40 years of operation, the pipelines of the flare system have corroded. Figure 1 illustrates the corroded areas. Reparation has been done by reconstitution of the surface by applying Belzona™ on corroded area as a recovery of lost metal. It is to be noted that the Belzona reparation is used just to reconstitute the affected area of the pipe by corrosion. It is considered as a coating used to stop the corrosion mechanism and protect the pipe. In the area with an important loss of metal characterised by a high wall thickness (WT), reinforcement by welding a plate has been done as shown in Fig. 2. This classical reparation method has been used as a coating in order to preserve the pipe and stop the corrosion process. For the reinforcement with plate, the flare system was stopped, causing the shutdown of the plant.

The prediction of failure pressure for the corroded cylindrical pipe before and after repair is critical to the reliability of natural gas transmission. In this order, a nonlinear numerical solution is developed for the repair of corroded pipelines without stopping operation and production loss. To achieve this goal, the following steps were taken:

- creation of an FEA corrosion model of a pipe X60, where the dimensions are similar to the pipe geometry used in the oil and gas plant (Figs. 1 and 2);
- the prediction of the failure pressure in the corroded pipe using nonlinear FEA is based on von-Mises yield criterion and some results are compared to the RSTRENG method and previous work, /24, 25/;
- study and discussion of the effects of length, width, and spacing of corrosion pits on failure pressure;
- prediction of failure pressure assessment for the corroded pipe reinforced with a composite patch;
- determination of the number of patch composite plies needed to avoid pipe failure.

Figure 1. Corrosion of the flare system pipeline (LPG plant).

Figure 2. Reparation of the corroded area.

FINITE ELEMENT MODELLING

Pipe geometry and material properties

In the present study, the estimation of failure pressure in the corroded pipeline under internal pressure is estimated using Abaqus/Standard© module.

A pipe of 508 mm in diameter and 5.7 mm wall thickness made of X60 steel is considered, where the material properties are illustrated in Table 1.

The aim of this step of the present study is to acquire results from a full scale rupture test of the pipe with an artificial corrosion defect, where flat-bottom corrosion and a uniform depth are applied at the centre of the corrosion. The dimensions of the pipe and defects are modelled as shown in Fig. 3. As shown in Fig. 4, the corroded pipe is analysed. In both cases, the corrosion is applied on outer pipe surface with smooth edges. Pipe and defect dimensions are summarized in Table 2.

Table 1. Properties of pipe steel X60, /23/.

Property	Value
Density, ρ (kg/m^3)	7850
Modulus of elasticity, E (GPa)	207
Poisson's ratio, ν	0.30
Yield strength, σ_Y (MPa)	435
Ultimate tensile strength, σ_U (MPa)	631

Table 2. Pipe dimensions and defect geometries.

Geometry	Value
Pipe diameter D (mm)	508
Wall thickness, t (mm)	5.7
Corrosion depth, d (mm)	2.016
Corrosion length, l (mm)	200
Corrosion width, w (mm)	30

Figure 3. Sectional view of pipeline with corrosion defect (not to scale).

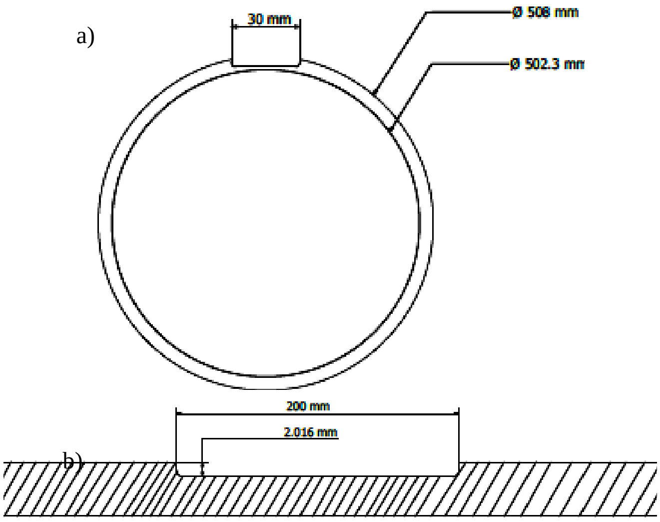


Figure 4. Sectional views of pipeline with corrosion defect (not to scale): a) cross-section through centre of corrosion; b) longitudinal section through centre of corrosion.

The affected area is characterised by a rectangular form in this study. Most important is to take the maximum depth of the corroded area during the assessment (2.016 mm in our case). The pipe is used to transport clean and non corrosive gas. So, there is no internal corrosion. This has been confirmed during pipe thickness measurement at preventive inspection.

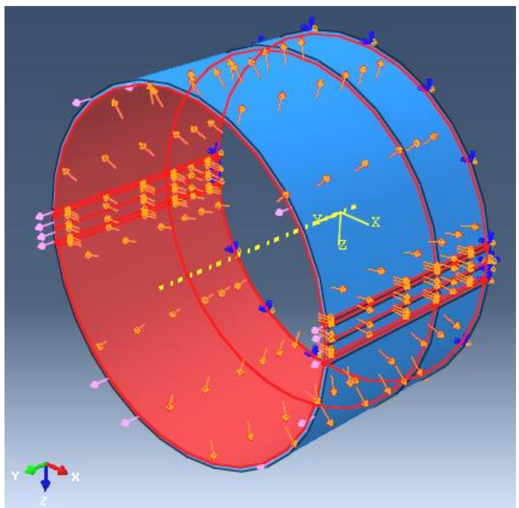
FE modelling and boundary condition

The finite element method (FEM) is considered to investigate the prediction of failure pressures of the corroded pipe. In our study, the finite element program ABAQUS© is used to model the corrosion defect and predict failure pressure based on average circumferential tensile test results, /26/.

In our model, as shown in Fig. 5, only half of the pipe is considered in order to take profit of the symmetry and reduce computation time. At the left end of the pipe, the boundary condition is applied symmetrically, and the point is fully restrained. Under applied loading, model stability is then ensured.

The internal pressure of the pipe is the applied loading, An equivalent axial load is simulated and supposed to be applied on the right end of the pipe.

a)



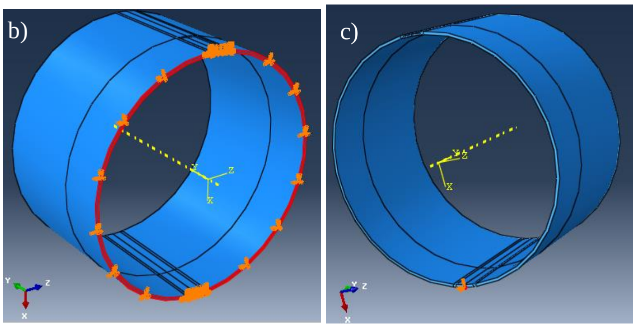


Figure 5. Boundary conditions and loading on the corroded pipe: a) applied loading; boundary conditions: b) symmetrical; c) bottom point fully restrained.

In our FE model, the pipe outer and inner diameters are equal to D_o and D_i, respectively. When the pipe is subjected to internal pressure P, the equivalent axial load is calculated using the axial tensile stress as follows:

$$\sigma_t = P\frac{D_i^2}{D_0^2 - D_i^2} . \quad (1)$$

In this study, mesh sensitivity of our FE model is analysed regarding the number of plies and the variation of global nodes as illustrated in Figs. 6 and 7. According to Fig. 7, we conclude that the estimated von Mises stress is the same for models with 3 to 9 plies. The mesh is the finest at the area of the corrosion defect and is progressively rarefied starting from the defect along the longitudinal and circumferential directions (Fig. 8). The optimal number of models is about 120 000.

According to the study of Fekete and Varga /25/, the lengths L of the FEA models have to be set in such manner to avoid local perturbation of the stress state. After the L_{min} longitudinal distance (damping distance), the effect of this perturbation still occurs but is not significant. This L_{min} distance is estimated using the following equation:

$$L_{min} = \frac{1}{2} + \frac{d}{t}\sqrt{Dtl} , \quad (2)$$

where: L_{min}-length of corrosion; d-depth of corrosion; t-thickness of pipe wall; D-diameter of pipeline.

For nonlinear FEA, we have used the Ramberg-Osgood equation, Eq.(3), from engineering stress-strain data in order to obtain the true stress-strain data:

$$\varepsilon = \frac{\sigma}{E} + \beta\left(\frac{\sigma}{\sigma_y}\right)^{n-1}\left(\frac{\sigma}{E}\right). \quad (3)$$

We have employed $\beta = 1.75$ and $n = 9$ and obtained the true stress-strain curve using a linear connection method. This true stress-strain data curve, representing elasto-plastic behaviour, is inserted into FE models to obtain the nonlinear analysis.

RESULTS AND DISCUSSION

Mesh sensitivity study

The number of elements in the model is increased by introducing more plies and calculating the corresponding von-Mises stress. When there is no change in the calculated von-Mises stress, we have considered that the corresponding meshing is enough for an accurate result.

According to the number of plies

Variation in the number of plies does not impact the obtained results since the von-Mises stress calculated is the same as shown in Fig. 6.

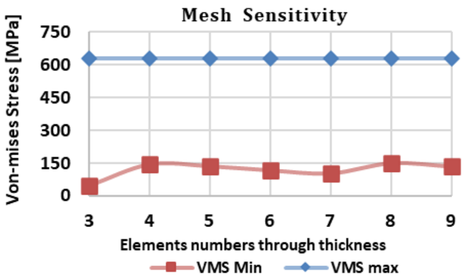


Figure 6. Von Mises stress calculated Vs. Elements number through thickness.

By limiting the number of plies, calculation time is significantly reduced. A reduction ratio of more or less 50 % is obtained.

According to the global seed

We have varied the global nodes from 35 to 12. It has been observed that from a global node of 13 and less, there is no change in von-Mises stress. The corresponding mesh contains approximately 110 000 elements. Mesh sensitivity regarding the variation of global nodes is illustrated in Fig. 7.

Defect width

From the existing models for burst pressure prediction of a corroded pipeline, we have noted that only length and depth of corrosion are employed in the calculation. Conventional FE analysis performed in developing the models showed no effects of defect width, /26/. As a result, the corrosion width is not used.

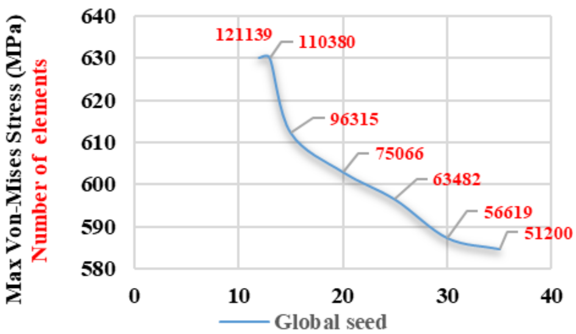


Figure 7. Von Mises stress vs. global seed and element number.

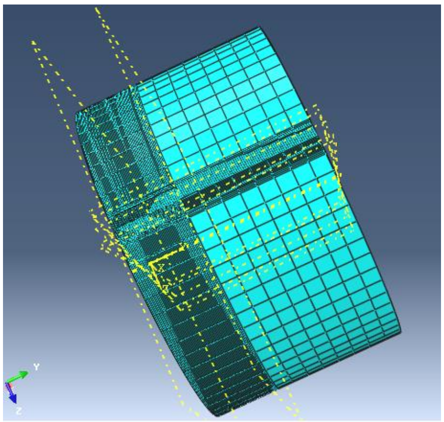


Figure 8. FE applied mesh.

A calculation of defect width is done to confirm this conclusion. The study concerns a corrosion defect of uniform depth modelled using FEM to estimate the max von-Mises stress. The corrosion defect model (45 % WT) is subjected to an internal pressure of 9.47 MPa. The obtained results are illustrated in Fig. 9. Referring to the figure, we conclude that there is no impact of corrosion defect width variation on the maximal calculated von-Mises stress. So, the failure pressure remains the same, and no change is noted for any corrosion defect width.

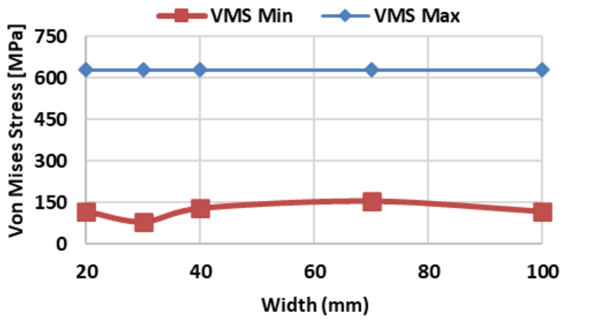


Figure 9. Corrosion width ratio vs. calculated von-Mises stress.

Failure pressure prediction and validation of FE model

For the corrosion modelling, a set of five longitudinally aligned simulated corrosion defects (grooves) of uniform depth are modelled using FEM to predict failure pressures. The evaluation concerns pipes with 200 mm long corrosion defects and depths of 22 %, 45 %, 61 %, 66 %, and 70 % WT, corresponding to experimental defect geometry consisting of a rectangular groove with a radius at corners, /27/.

Figure 10 shows a typical corrosion defect model (61 % WT) subjected to internal pressure of 7.3 MPa.

When the stress at defect bottom reaches the circumferential ultimate true stress of 631 MPa, the initiation of failure occurs, and the prediction is done. Failure pressure is indicated by the intersection between the maximal von Mises stress and ultimate true stress, as illustrated in Fig. 11.

From the curves in Fig. 11, we obtain failure pressures of the pipe under internal pressures. Failure pressures are 6, 6.6, 7.3, 9.47, and 12.2 MPa, for corrosion depths of 70 %, 66 %, 61 %, 45 %, and 22 %, respectively.

The confrontation of the above results with those obtained experimentally by Bedairi et al. /24/ has been done and is illustrated in Fig. 12.

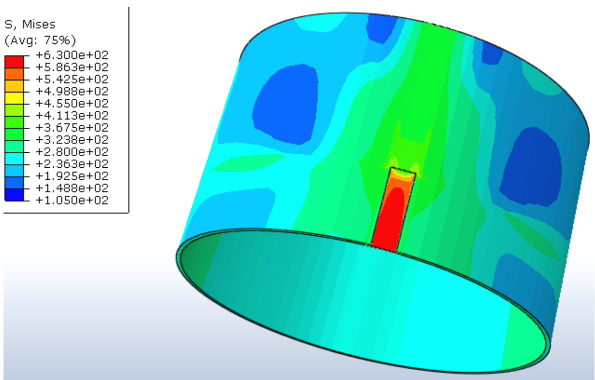


Figure 10. The 61 % WT corrosion defect model (effective stress contours, 7.3 MPa internal pressure).

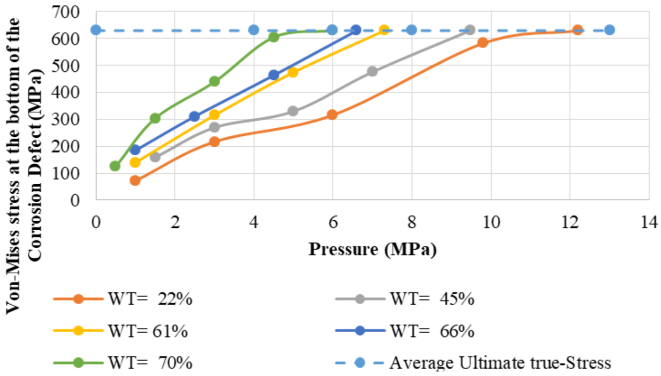


Figure 11. FE analysis of corrosion defects (different depths).

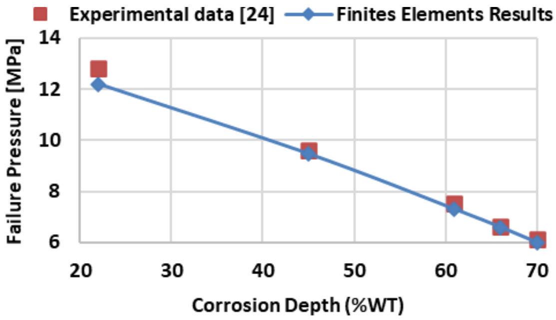


Figure 12. Validation of FE predicted failure pressure.

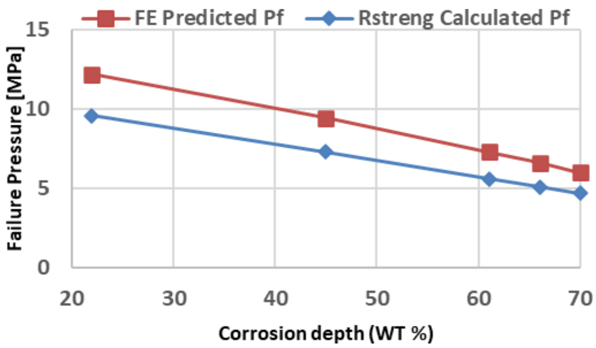


Figure 13. Prediction of failure pressure by nonlinear FEA validated by RSTRENG method results.

Failure pressures of the corroded pipe are practically the same for corrosion depth ranging from 40 % to 70 %. Between 22 % and 40 %, there is a small difference. From this comparison, we can conclude that the proposed model in this study is validated and will be considered during the step related to pipe repair by patch reinforcement.

Failure pressure has also been predicted in this study by using the RSTRENG method. It is noted that, in general, the RSTRENG predicted failure pressure values are consistently lower than those predicted using the FE method. Figure 13 shows this statement and confirms the above findings reported in a lot of literature. This is another validation of the model proposed in the present study.

The calculations permit to conclude that there is no failure of the corroded pipe reinforced by composite patch (even for a WT of 70 %). This efficient reparation permits a safety pipeline operation.

Reparation by reinforcement of the corroded pipe

As mentioned in different studies and research, the repair of corrosion and cracks requires labour, time, and expense if we decide to use the classical method of reparation based on the replacement of the damaged pipe.

For this reason, the second part of our study involves the analysis of corroded thin-walled metallic pipes reinforced with composite patches. The goal is to propose reinforcement of the damaged area by a composite patch and estimate the necessary geometry and material to avoid pipe failure.

Patches proposed for these reinforcements are made from synthetic composite (glass fibre and epoxy resin), /28/, and biocomposite (polyester reinforced with natural fibres: polyester/jute). Mechanical properties and geometrical dimensions of both adhesive and patches are shown in Table 3.

Table 3. Mechanical properties and dimensions of synthetic and biocomposite patch.

	Thickness (mm)	Length (mm)	Mechanical properties
Synthetic composite	0.4	100	E_1= 148000 MPa, $E_2 = E_3$ = 9200 MPa $\nu_{12} = 0.27$, $\nu_{13} = \nu_{23} = 0.3$ $G_{12} = G_{13}$ = 5300 MPa, G_{23} = 2300 MPa
Bio composite	1	100	E_1 = 4500 MPa, $E_2 = E_3$ = 5000 MPa $\nu_{12} = 0.24$, $\nu_{13} = \nu_{23} = 0.27$ $G_{12} = G_{13}$ = 1450 MPa, G_{23} = 1960 MPa
Adhesive	0.2	100	E_c = 2250 MPa, $\nu_c = 0.3$

Reinforcement by synthetic composite patch

The corroded pipe model considered in this analysis is submitted to internal pressure of 9.47 MPa and 45 % WT, which gives a corrosion thickness equal to 2.565 mm.

The maximal von-Mises stress is calculated for five stacking sequence repaired pipe models (Table 4).

Table 4. Stacking sequences of synthetic composite patch.

Stacking sequence	Orientation angle
Seq 1	[0°/90°/0°]
Seq 2	$[0°/90°]_2$
Seq 3	$[[0°/90°]_2/0°]$
Seq 4	$[0°/90°]_3$
Seq 5	$[[0°/90°]_3/0°]$

Stacking sequence synthetic patch effect on von-Mises stress

Below is the result obtained for the model with a Seq2 patch. Figure 14 illustrates the von-Mises stress obtained. For the pipe, the maximal Von Mises stress obtained is 452.4 MPa, representing 71.7 % of average ultimate true stress (631 MPa). Then, the failure of the repaired part will not occur at the internal pressure of 9.47 MPa.

For the other models, Table 5 presents results obtained for different stacking sequences. These results are represented and compared to the corroded pipe in Figs. 15 and 16. Other stacking sequences can also be considered and used.

Table 5. Maximum Von-Mises Stress of the repaired pipe.

Stacking Sequence	Seq1	Seq2	Seq3	Seq4	Seq5
Max Von-Mises Stress (MPa)	481	466	452	444	437

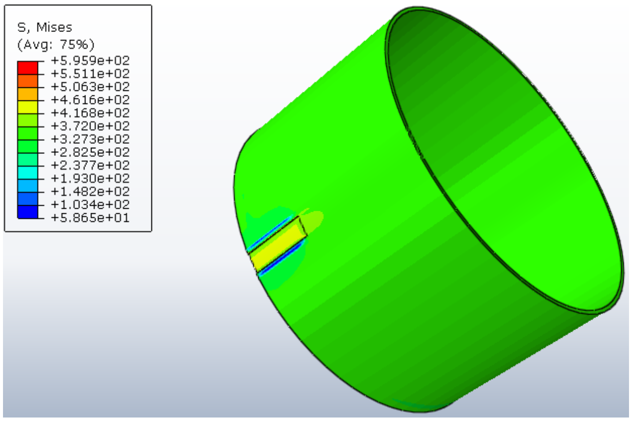


Figure 14. The 45 % WT corrosion defect model repaired with Seq2 patch.

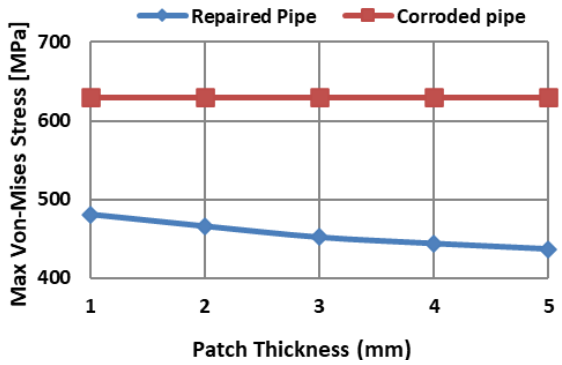


Figure 15. Maximal von-Mises stresses of corroded pipe compared to the repaired pipe.

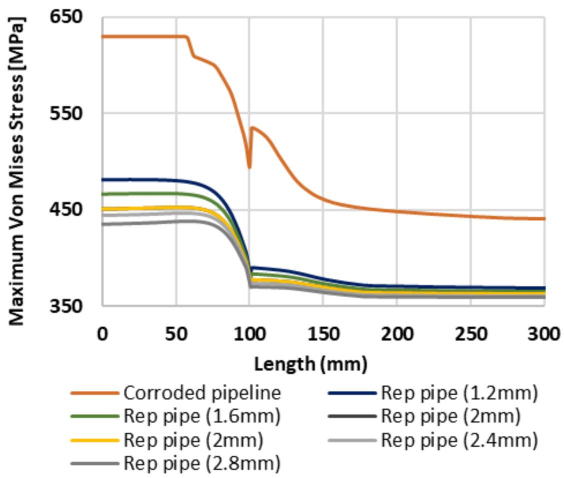


Figure 16. Comparison of von-Mises stress for corroded and repaired pipe.

Reinforcement by composite patch gives good results, but these are not guaranteed over time with the degradation of mechanical properties of composites under the effect of moisture absorption. Two solutions are proposed to avoid this risk:

- replace the patch after a limited period, depending on the mechanical properties degradation caused by the moisture absorption;
- provide a patch with an additional thickness.

Effect of increasing internal pressure

The aim of this step of our study is to determine the limit of reinforcement given by repairing the corroded pipe using the patch. The model of a pipe with a Seq1 patch of 1.2 mm in thickness and subjected to internal pressure of 9.47 MPa is considered. Internal pressure increases by a successive rate of 10 %, and corresponding von-Mises stresses are calculated. The results are illustrated in Table 6.

Table 6. Maximal von-Mises stress of the repaired pipe.

Internal pressure (MPa)	$1\times P_{int}$	$1.1\times P_{int}$	$1.2\times P_{int}$	$1.3\times P_{int}$	$1.4\times P_{int}$	$1.5\times P_{int}$
	9.47	10.42	11.4	12.31	13.26	14.21
von-Mises stress (MPa)	481	521	546	572	594	610

Reinforcement by synthetic composite patch

For the biocomposite patch, we have varied patch thickness and calculated the equivalent maximal von-Mises stress in the corroded area. We obtained the following results for the internal pressure loading of 13.26 MPa, given in Table 7.

Table 7. Maximal von-Mises stress of pipe repaired by biocomposite patch.

BC patch thickness (mm)	2	3	4	6	8	10
Max Von Mises Stress (MPa)	630	604	591	575	565	553

Interpretations

- The evolution of von-Mises stress is identical for corroded and repaired pipe. Maximal and minimal von-Mises stresses are present in the same area for both corroded and reinforced pipes.
- The maximal values are obtained in the corroded area, i.e., where there is a loss of material equal to 45 % of the pipe wall thickness (WT).
- With reparation by patch, there is a significant reduction of von Mises stress on the pipe. The maximal values do not reach 500 MPa. This von-Mises stress decrease is equivalent to more or less 20 %. Pipe failure is then totally avoided.
- When patch thickness or number of patch layers increases, the pipe's resistance to failure also increases, confirming the efficiency of this reparation type. An analytical correlation between the plies number (patch thickness) and corrosion wall thicknesses can be done. Obtaining these results optimizes the repair of corroded pipes and provides support for the maintenance department.
- Reparation by a synthetic composite patch of 1.2 mm thickness offers a real reinforcement for the corroded pipe by increasing resistance to failure. The same reinforcement is obtained using a biocomposite patch but of 3 mm thickness which represents two and a half of the synthetic composite patch thickness offering the same resistance to the corroded pipe.
- The obtained results show a maximal von-Mises stress of 610 MPa for an internal pressure of 150 % of the initial value, i.e. failure is avoided at 14.21 MPa (1.5×9.47 MPa).

CONCLUSIONS

In this paper, a corroded pipeline with a single corrosion pit before and after being repaired by synthetic and natural composite fibres is investigated by using the finite element method, and the effects of the length, width, and spacing of corrosion pits on failure pressure are discussed.

For the nonlinear numerical model proposed in this study, we have considered the circumferential ultimate true stress of 631 MPa for a 508 mm diameter and 5.7 mm wall thickness pipe as the failure criteria. The failure initiation of the corroded pipe occurred when the von Mises stress reached 631 MPa.

Corrosion defects, represented by blunt grooves (22 %, 45%, 61 %, 66 %, and 70 % WT in depth, 200 mm length), were evaluated using the above criteria after the numerical evaluation of von-Mises stress of the corroded pipe subjected to different internal pressures. The results of the developed FEM are in good agreement with experimental data.

The failure pressures predicted using FEM were consistently higher than those predicted by the RSTRENG method. This statement confirms the conservative aspect of this method as reaffirmed in previous studies and research.

For the reparation of the corroded pipe with a corrosion defect of 45 % WT, the reinforcement by composite patch has been numerically analysed for five patch sequences with different plies number and orientation angles.

The reinforcement by biocomposite is also examined and the results obtained are very interesting after confirming that the corroded pipe can resist when just a 3 mm natural patch thickness is used.

At this step of elasto-plastic analysis, the numerical model is reliable and can be employed as a basis for the prediction of the failure pressure of corroded natural gas transmission pipelines and optimisation of patch composite repair.

REFERENCES

1. NTSB/SS-15/01, Integrity Management of Gas Transmission Pipelines in High Consequence Areas, National Transportation Safety Board, Washington, DC, USA, 2015.
2. Shamsuddoha, M., Islam, M.M., Aravinthan, T., et al. (2013), *Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs*, Compos. Struct. 100: 40-54. doi: 10.1016/j.compstruct.2012.12.019
3. Chen, J., Pan, H. (2013), *Stress intensity factor of semi-elliptical surface crack in a cylinder with hoop wrapped composite layer*, Int. J Press. Ves. Pip. 110: 77-81. doi: 10.1016/j.ijpvp.2013.04.026
4. Alexander, C.R. (2007), *Guideline for repairing damaged pipelines using composite materials*, Paper no. 07144, NACE Int. 2007 Corrosion Conf. & Expos., 2007, Nashville, TN, USA.
5. Duell, J.M., Wilson, J.M., Kessler, M.R. (2008), *Analysis of a carbon composite overwrap pipeline repair system*, Int. J Press. Ves. Pip. 85(11): 782-788. doi: 10.1016/j.ijpvp.2008.08.001
6. McGeorge, D., Echtermeyer, A.T., Leong, K.H., et al. (2009), *Repair of floating offshore units using bonded fibre composite materials*, Compos. Part A: Appl. Sci. Manuf. 40(9): 1364-1380. doi: 10.1016/j.compositesa.2009.01.015
7. Turton, T.J., Dalzel-Job, J., Livingstone, F. (2005), *Oil platforms, destroyers and frigates-case studies of QinetiQ's marine composite patch repairs*, Compos. Part A: Appl. Sci. Manuf. 36(8): 1066-1072. doi: 10.1016/j.compositesa.2004.11.006
8. Cheng, J., Wu, X., Li, G., et al. (2007), *Design and analysis of a smart composite pipe joint system integrated with piezoelectric layers under bending*, Int. J Solids Struct. 44(1): 298-319. doi: 10.1016/j.ijsolstr.2006.04.021
9. Hocine, A., Maizia, A., Ghouaoula, A., Dehmous, H. (2018), *Reliability prediction of composite tubular structure under mechanical loading by finite element method*, J Fail. Anal. Preven. 18: 1439-1446. doi: 10.1007/s11668-018-0536-z

10. Ghouaoula, A., Hocine, A., Chapelle, D., et al. (2018), *Analytical prediction of behaviour of damaged composite tubular structures under quasi-static pressure*, Struct. Integ. Life, 18(2): 143-148.
11. Habbar, G., Maizia, A., Hocine, A., et al. (2022), *Micromechanical analysis of a bio-sandwich application for cylinder under pressure*, J Compos. Sci. 6(3): 69. doi: 10.3390/jcs6030069
12. Cosham, A., Hopkins, P., Macdonald, K.A. (2006), *Best practice for the assessment of defects in pipelines - Corrosion*, Eng. Fail. Anal. 14(7): 1245-1265. doi: 10.1016/j.engfailanal.2006.11.035
13. Teixeira, A.P., Soares, C.G., Netto, T.A., Estefen, S.F. (2008), *Reliability of pipelines with corrosion defects*, Int. J Press. Ves. Pip. 85(4): 228-237. doi: 10.1016/j.ijpvp.2007.09.002
14. Caleyo, F., González, J.L., Hallen, J.M. (2002), *A study on the reliability assessment methodology for pipelines with active corrosion defects*, Int. J Press. Ves. Pip. 79(1): 77-86. doi: 10.1016/S0308-0161(01)00124-7
15. ASTM B31G-2009, Manual for Determining the Remaining Strength of Corroded Pipelines, Suppl. To ASME B31 Code for Pressure Piping, ASME, USA.
16. Kiefner, J.F., Vieth, P.H. (1990), *Evaluating pipe: new method corrects criterion for evaluating corroded pipe*, Oil Gas J, 88 (32): 56-59.
17. Kiefner, J.F., Vieth, P.H. (1990), *Evaluating pipe conclusion: PC program speeds new criterion for evaluating corroded pipe*, Oil Gas J, 88(34): 91-93.
18. Veritas Det Norske (2004), DNV Recommended practice, RP-F10, Corroded Pipelines.
19. DNV, DNV-RP-F101: Corroded Pipelines 2010: Norway.
20. Chai, J., Lv, Z., Zhang, Z., et al. (2022), *Nonlinear failure analysis on pressurized cylindrical shell using finite element method: Comparison of theoretical and experimental data*, J Fail. Anal. Preven. 22: 1000-1010. doi: 10.1007/s11668-022-01378-w
21. Abdalla Filho, J.E., Machado, R.D., Bertin, R.J., Valentini, M.D. (2014), *On the failure pressure of pipelines containing wall reduction and isolated pit corrosion defects*, Comp. Struct. 132: 22-33. doi: 10.1016/j.compstruc.2013.10.017
22. Wang, T., Yang, J.G., Liu, X.S., et al. (2012), *Stress intensity factor expression for butt joint with single-edge crack considering the effect of joint shape*, Mater. Design, 36: 748-756. doi: 10.1016/j.matdes.2011.12.020
23. Mondal, B.C., Dhar, A.S. (2019), *Burst pressure assessment of corroded pipelines using fracture mechanics criterion*, Eng. Fail. Anal. 104: 139-153. doi: 10.1016/j.engfailanal.2019.05.033
24. Bedairi, B., Cronin, D., Hosseini, A., Plumtree, A. (2012), *Failure prediction for Crack-in Corrosion defects in natural gas transmission pipelines*, Int. J Press. Ves. Pip. 96-97: 90-99. doi: 10.1016/j.ijpvp.2012.06.002
25. Fekete, G., Varga, L. (2012), *The effect of the width to length ratios of corrosion defects on the burst pressures of transmission pipelines*, Eng. Fail. Anal. 21: 21-30. doi: 10.1016/j.engfailanal.2011.12.002
26. Tyson, W. (2005), Assessment of Crack Defects, Banff Pipeline Workshop.
27. Hosseini, A., Cronin, D., Plumtree, A., Kania, R. (2010), *Experimental testing and evaluation of crack defects in line pipe*, Proc. 8th Int. Pipeline Conf. 2010, Calgary, Alberta, Canada, Paper no: IPC2010-31158, pp.275-285. doi: 10.1115/IPC2010-31158
28. Maligno, A.R., Warrior, N.A., Long, A.C. (2010), *Effects of interphase material properties in unidirectional fibre reinforced composites*, Compos. Sci. Technol. 70(1): 36-44. doi: 10.1016/j.compscitech.2009.09.003