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Numerical Study of a Cracked Pipe Before And After Using Two Different Repair Methods

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Keywords：pipeline, fracture, repair, pressure.

ABSTRACT

Pipelines are the cheapest and safest way to transfer fluids in industry. The operation of pipelines, on the other hand, raises the risk of failures such as internal and exterior corrosion, cracking, and warping. It should be noted that non-destructive testing guarantees the correct operation of pipelines before and after failures. As a result, when damage occurs, it is important to fix it in order to avoid loss of life and material. In our study, we generated an external fracture in a pipeline by using the API X80M as the construction material. We then performed a comparative numerical analysis using the ANSYS software, simulating two methods of repair, the first using a half-shell and the second using a composite patch (epoxy carbon). The Von Mises stresses and stress intensity variables were really the parameters considered in our investigation.

INTRODUCTION

The prediction of fractures, as well as the durability and safety of pipelines, are essential in many practical transportation applications, such as hydrocarbon distribution (Miller, 1988; Kim, 2003). The erosion or complete decomposition of these pipelines over time, depending on the corrosive media, will result in very significant economic losses (Arav, 1997). Fracturing, which may take various forms, is one of the most hazardous issues. Depending on their direction, cracks can be classified as longitudinal or transverse (Mahdi et Hasnaoui, 2018). It is well known in fracture mechanics that the development of a crack is mostly determined by the stress state and the local strain near the crack tip. When the effects of plasticity are significant, the modeling of fracture propagation must take into consideration the material's actual behavior. Any particle entry into significant fractures under cyclic loading might cause pipeline damage and burst (Brekke, 1986).

There is always a risk of pipeline damage due to different situations such as corrosion, structural defects, and ground movement (Zedadma et Khallaf, 2018; Khireche et Labed 2018). There are numerous sorts of pipeline repairs that may be performed to extend their life. In this case, we employed two distinct repair procedures (half-shell welding and composite patch repair), the objective of which is to decrease or eliminate the fracture in terms of resistance and service life of the pipe. Our task is to find the most effective repair procedure possible in order to avoid any damage or rupture of the fractured pipe. We have three elements: The first step was to determine the Von Mises stresses of an ideal tube as the internal pressure is varied. The second portion displays the results of a cracked tube in order to calculate its resistance limit based on the stress intensity factor. To avoid any damage or rupture, we repaired, either with a composite patch or a half-shell. In the third section, we provide the Von Mises stresses and stress intensity factor findings, which will help us to choose the optimum repair strategy.

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UNCRACKED PIPE

We consider a pipeline made of **API X80M** material to be linearly elastic, with the following mechanical properties:

Table1. Mechanical properties of ISO 3183 X80M steel (Santos, Hermenegildo, Afonso, Marinho, Paes et Ramirez, 2010)

Properties	MPa	Ksi
Yield strength (YS)	568	82
Tensile strength (TS)	686	100
YS/TS (%)	83	
% Elongation	44	
Average micro-hardness (HV0.2)	235	

Geometry the tube

On a pipeline with an internal diameter of 722 mm, a thickness of 10 mm, and a length of 1000 mm, we applied four different pressures (5, 6, 7, and 8 MPa). We a test of "grid-independence" to find a proper mesh size, as shown in Fig. 1

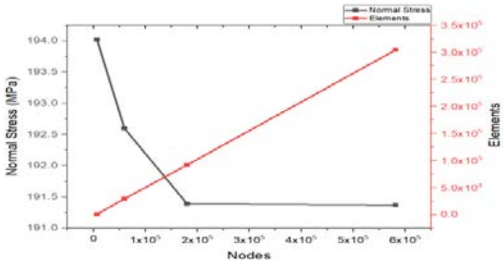

Fig. 1 The grid-independence

- Stress results line become horizontal that show mesh independence.
- Allowable change under 1 %.
- Increasing in elements number according to normal stress and nodes number.

The following graphs illustrate the results of the ideal pipe pipeline simulation:

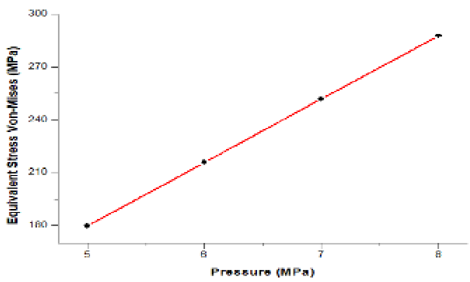

Fig. 2(a) Equivalent (Von-Mises) Stress

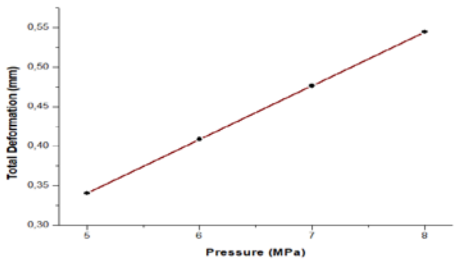

Fig. 2(b) Total Déformation

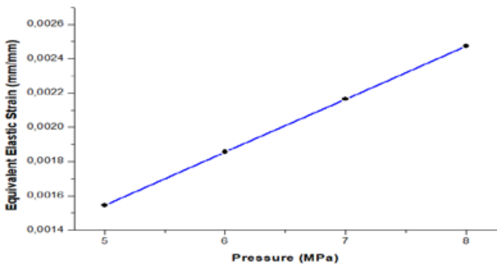

Fig. 2(c) Equivalent Elastic Strain

It is observed that Von Mises stress varies proportionately to internal pressure. Furthermore, the pipeline is in the elastic domain since the Von Mises stress at 8MPa pressure is less than the elastic limit. Deformations range from 0.34 mm (lowest value) to 0.54 mm (highest value).

The corresponding elastic stresses have very small values ranging from 0.0015 to 0.0024, making them virtually insignificant.

CRACKED PIPE

On the pipeline, we generated a semi-elliptical external fracture, the parameters and features of which are shown in the table below:

Table2. Information on the semi-elliptical crack

Definition	
Crack Shape	Semi-Elliptical
Major Radius	5. mm
Minor Radius	3. mm
Mesh Method	Tetrahedrons
Largest Contour Radius	1. mm
Element Size	Default (0.10071 mm)
Mesh Contours	6
Solution Contours	Match Mesh Contours

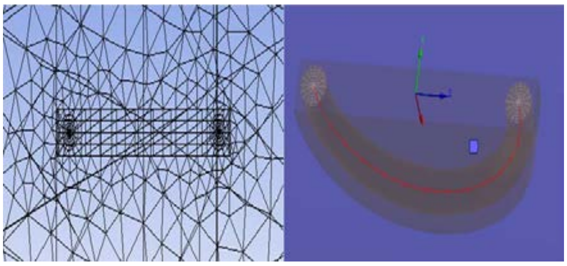

Fig. 3 Tetrahedral mesh and contours presentation (Zitouni et Labed, 2021)

We used the same pressures that were tested in the same geometry tube. The goal of this method is to determine the impact of the highest pressure that our fractured pipe can resist. The Von Mises stress and the stress intensity factor are two strength criteria.

The results of this test are represented in the figures below.

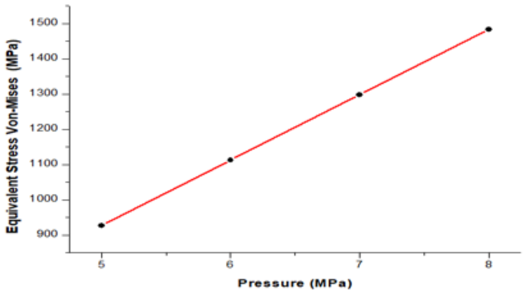

Fig. 4(a) Equivalent (Von-Mises) Stress

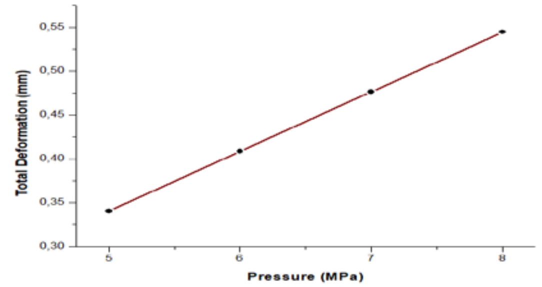

Fig. 4(b) Total Deformation

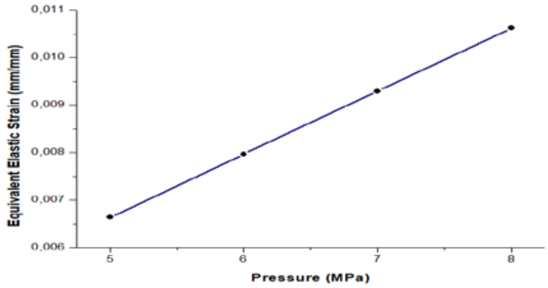

Fig. 4(c) Equivalent Elastic Strain

With the presence of the fracture and following Fig. 4 (a), we can see that the Von Mises stress has grown significantly and is now larger than the elastic limit for the lowest pressure. We may assume that the pressure of our fractured pipe can bear is less than 5 MPa. Beyond this value, the pipeline is expected to be damaged or to break suddenly.

Stress intensity factor

George R. Irwin, widely recognized as the father of fracture mechanics, invented the stress intensity factor in 1957 (Irwin, 1957). It is one of the most basic and relevant factors in all fracture mechanics, and it is the sole essential parameter for determining the state of stress and strain in a crack (Fiordalisi, 2014). The variable K represents the Stress Intensity Factor (SIF). The stress intensity factor characterizes the stress condition near the fracture tip. It is proportional to the rate of crack development and is used to determine fracture failure criteria (Irwin, 195; S. Fiordalisi, 2014; Westergaard, 1939).

K was defined by Irwin as a near approximation to the crack tip of Westergaard full solution for the stress field surrounding a fracture (Westergaard, 1939). Westergaard employed complicated numbers and the Airy stress function. Erwin discovered that the combination of and accurately reflected the severity of the stress condition at the crack tip, and while he did not include the value at first, it was subsequently added to get the following formula:

$$K = \sigma_{\infty}\sqrt{\pi a} \qquad (1).$$

The figures below represent the stress intensity factors K_I and K_{II} from our study of the six contours for the four applied pressures (5MPa, 6MPa, 7MPa and 8MPa).

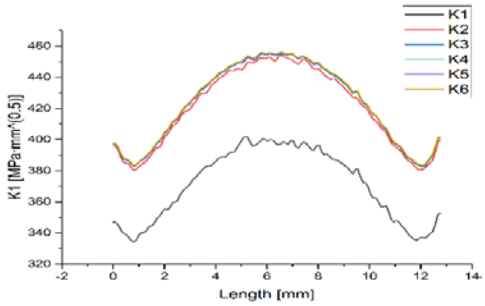

Fig. 5(a) K_I P = 5 MPa

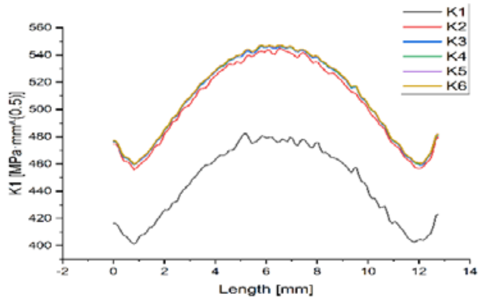

Fig. 5(b) K_I P = 6 MPa

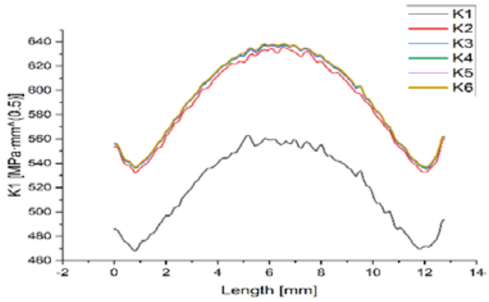

Fig. 5(c) K_I P = 7 MPa

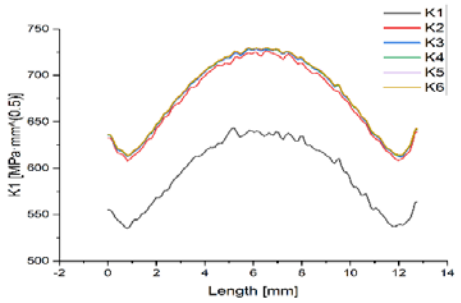

Fig. 5(d) K_I P = 8 MPa

With the exception of the first contour K_I, which has a lower value in contrast to the other contours, the contour curves are symmetrical with regard to the length of the semi-elliptical crack. Plasticization occurs as the applied internal pressure rises due to sudden cracking.

The contours of the stress intensity factor in mode II are then depicted in the figures below. For each pressure variation, the greater value corresponds to the first contour in mode II, as opposed to the SIF in mode I. In Mode II, the SIF values for all five contours are nearly identical.

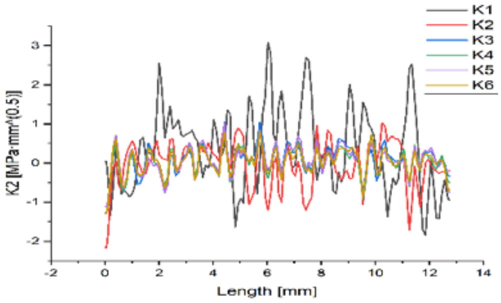

Fig. 6(a) K_{II} P = 5 MPa

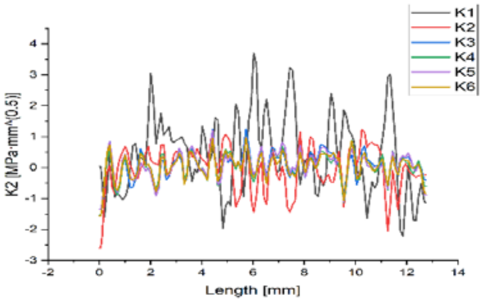

Fig. 6(b) K_{II} P = 6 MPa

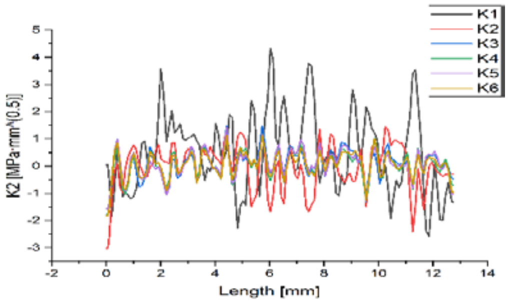

Fig. 6(c) K_{II} P = 7 MPa

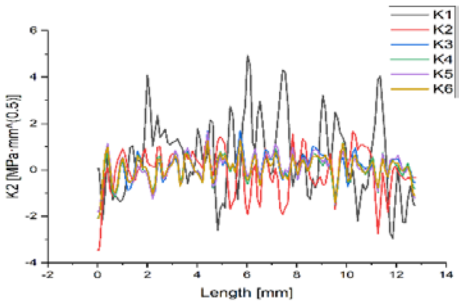

Fig. 6(d) K_{II} P = 8 MPa

Based on the findings obtained for different pressures (Fig. 5), it can be inferred that repair is required in the event of minimal pressure. We will suggest two repair methods, and the results will allow us to select the most successful repair method.

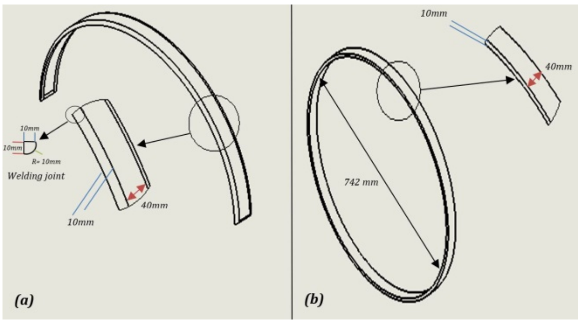

Fig. 7 Geometry of the two repair methods, (a). Repair of Half-Shell; (b). Repair by Composite Patch.

REPAIR OF HALF-SHELL

This repair procedure entails inserting welded half-shells to manage the pipes that transport hydrocarbons in order to minimize potential leaks, and is therefore used to repair axial or circumferential through or non-through defects (Fodil et Aous, 2018). There are experimental works of this type of repair like the article of (Chapetti, M., Otegui, J., Manfredi, C., and Martins, C., 2001)

Fig. 8 Half-shell welding operation (A. Benlekhal, 2010)

In the third section of our work, we made a repair using a half-shell of the same X80M material as the pipeline, welded with an **AA R610** weld bead, the mechanical characteristics are displayed in the table below:

Table3. Mechanical properties of AA R610 (Huissen., CEWELD, 2018)

Properties	MPa
Yield strength (YS)	620
Tensile strength (TS)	830
Young's Modulus	200000 MPa
Poisson's Ratio	0.3
Bulk Modulus	166670 MPa
Shear Modulus	76923 MPa

Fig. 9 represent the results of the simulation:

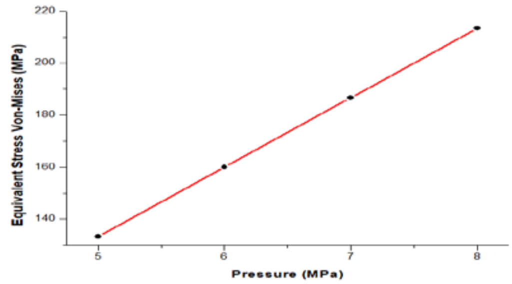

Fig. 9(a) Equivalent (Von-Mises) Stress

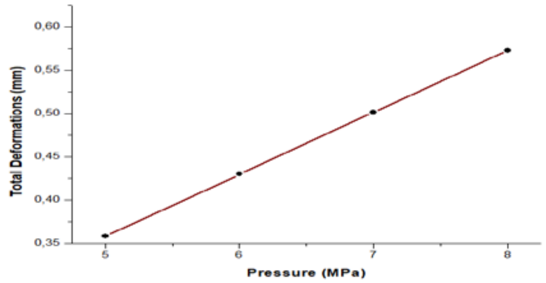

Fig. 9(b) Total Deformation

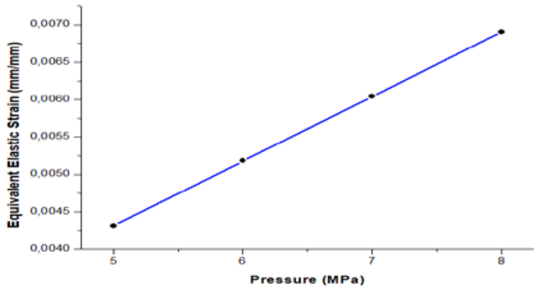

Fig. 9(c) Equivalent Elastic Strain

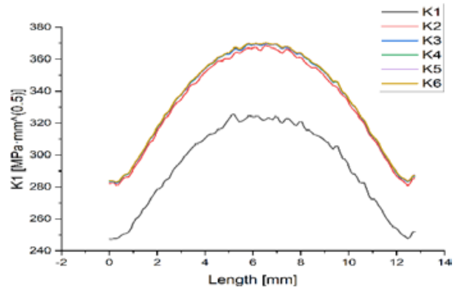

Fig. 10(b) K_I P = 6 MPa

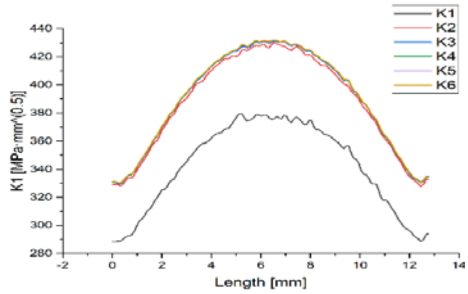

Fig. 10(c) K_I P = 7 MPa

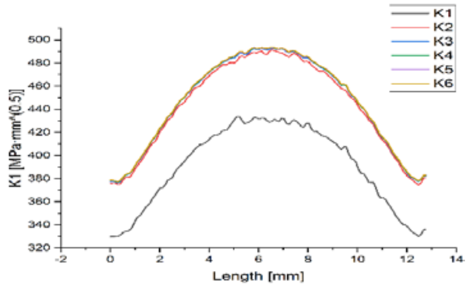

Fig. 10(d) K_I P = 8 MPa

Fig. 9 show the effect of half-shell repair giving the pipeline extra life. We discovered that after the half-shell repair, the Von-Mises stresses were reduced by 86 percent when compared to the findings of the pipeline without repair.

By comparing Fig 2 (b) and Fig 9 (b) the deformation curves and the results are almost the same in both situations between 0.35 mm and 0.60 mm after applying the same 4 different pressures (without repair and with repair).

The K_I are shown in the graphs below:

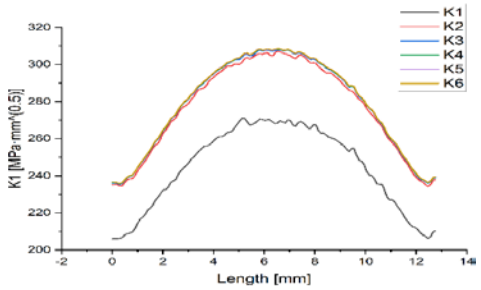

Fig. 10(a) K_I P = 5 MPa

The shape of the curves in this case with the half-shell repair is almost identical to the shape of the curves in the case of a cracked pipeline, the difference being that the values of the stress intensity factors K_I decrease almost by 66 percent when we apply pressure of 5 MPa, and the percentage decrease of the values of the factors becomes 40 percent with the other three pressures. It is noticed that the distribution of the curves is the same, with a significant drop in the level of Von Mises equivalent stresses.

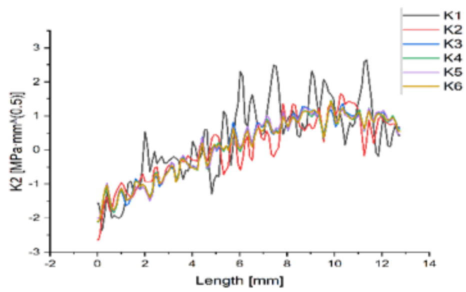

Fig. 11(a) K_{II} P = 5 MPa

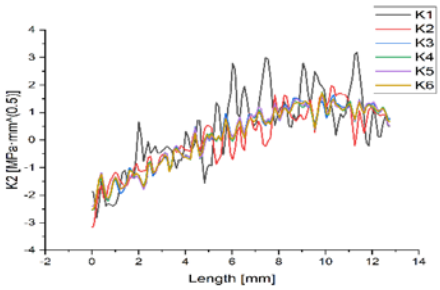

Fig. 11(b) K_{II} P = 6 MPa

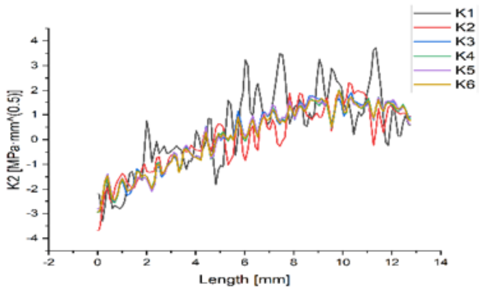

Fig. 11(c) K_{II} P = 7 MPa

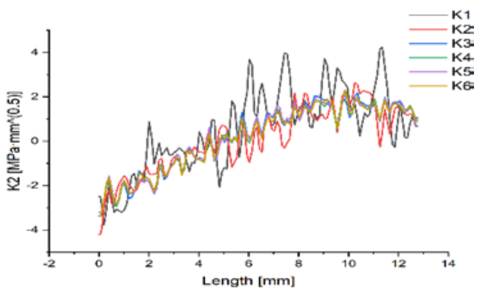

Fig. 11(d) K_{II} P = 8 MPa

REPAIR BY COMPOSITE PATCH

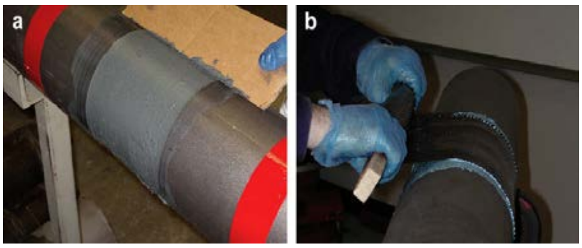

Fig. 12. Pipe repair process (a) filling defect with putty (b) wrapping epoxy wetted carbon fabric around the defect (Duell et Wilson, 2008).

This technique of repair is part of the damaged structure, particularly pipeline maintenance. New repair methods based on composite materials are being developed to slow the spread of cracks and increase the life of these structures. Indeed, because to their high specific mechanical characteristics and variety, composite materials and adhesives are increasingly being utilized to repair structures, with applications peaking around the end of the 1970s (Baghdadi, 2021).

We selected epoxy carbon for the composite patch repair, and its properties are as follows:

Table 4. Mechanical properties of epoxy carbon (Abdelouahed et Benzaama, 2019)

Young's Modulus X direction (MPa)	Young's Modulus Y direction (MPa)	Young's Modulus Z direction (MPa)
1.34e+005	10300	10300
Poisson's Ratio XY	Poisson's Ratio YZ	Poisson's Ratio XZ
0.33	0.33	0.53
Shear Modulus XY (MPa)	Shear Modulus YZ (MPa)	Shear Modulus XZ (MPa)
5500	5500	3200

The reparation white composite patch (epoxy/carbon) it is a popular method like the half-shell; there are also many experimental works of its own, such as (Duell, J.M., Wilson, J.M., and Kessler, M.R., 2008).

After the simulation we have the following results:

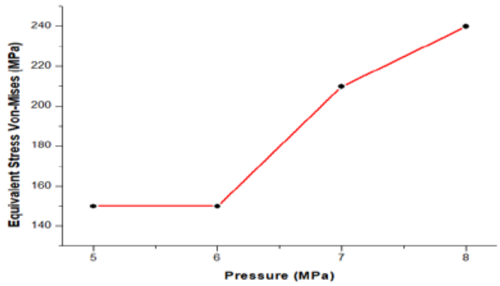

Fig. 13(a) Equivalent (Von-Mises) Stress

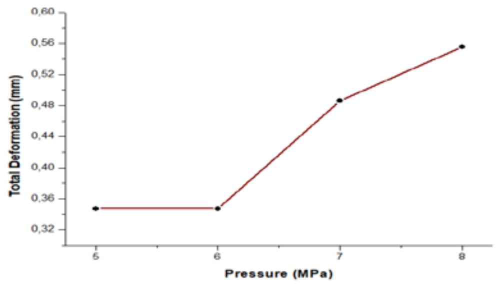

Fig. 13(b) Total Deformation

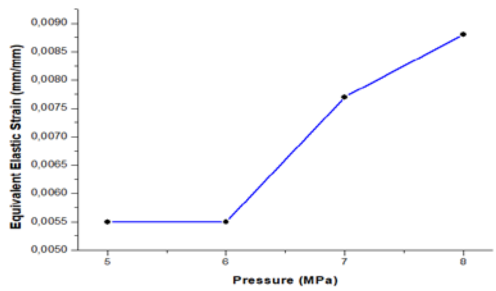

Fig. 13(c) Equivalent Elastic Strain

After the patch repair we have this time an almost 84% reduction in Von-Mises stresses, and almost 8% compared to the half-shell repair. In addition, the Von Mises stress is constant for the two pressures 5 MPa and 6 MPa.

The K_I and K_{II} are on the following curves:

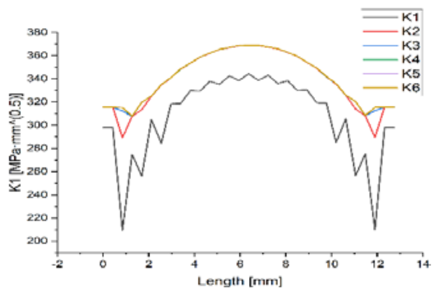

Fig. 14(a) K_I P = 5 MPa

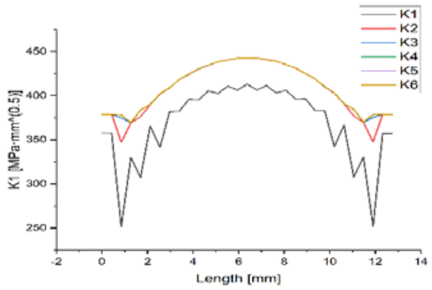

Fig. 14(b) K_I P = 6 MPa

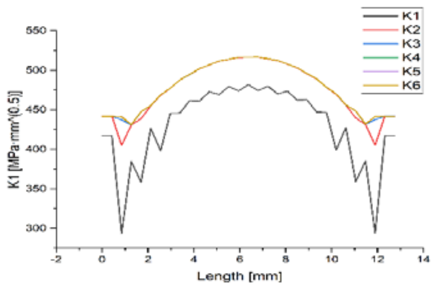

Fig. 14(c) K_I P = 7 MPa

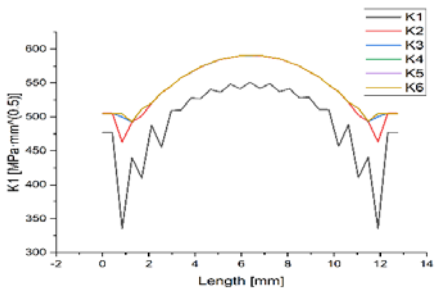

Fig. 14(d) K_I P = 8 MPa

The contour of K_I curves in the Patch repair is completely different from the other curves in the two prior examples, and we also observe that the four curves are symmetrical.

Compare the maximum values of K_I in this case with the case of repair by half-shell; we have an increase of almost 12% for the pressure 5 MPa, 16% for 6 and 8 MPa and 22% for 7 MPa.

The most remarkable thing in the results of Fig. 10 for the values of the SIF is the symmetrical appearance for the four pressures applied.

The comparison between the K_I of this repair with the K_I of cracked pipeline, we have a decrease of 19% for the three pressures 5, 6, 8 MPa and of 9% for 7 MPa.

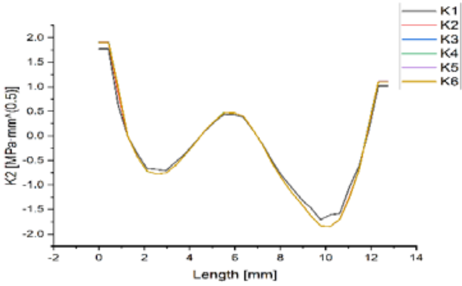

Fig. 15(a) K_{II} P = 5 MPa

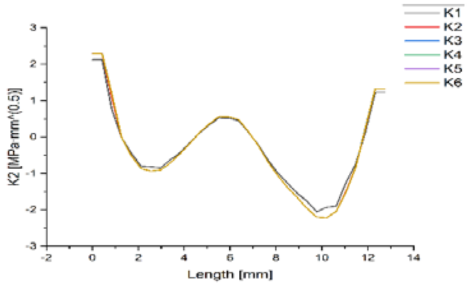

Fig. 15(b) K_{II} P = 6 MPa

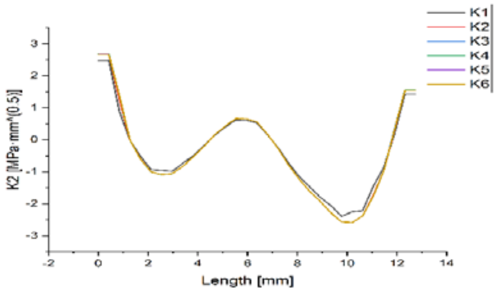

Fig. 15(c) K_{II} P = 7 MPa

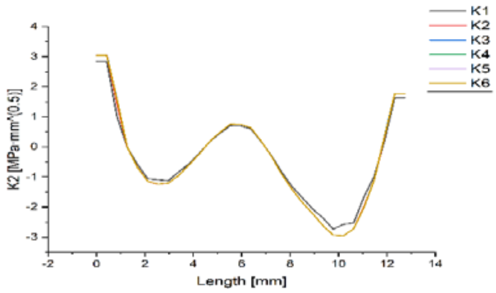

Fig. 15(d) K_{II} P = 8 MPa

We can see that the values of K_{II} are decreasing after Patch's repair.

We can say that all the contours of the SIF in mode II overlap, we can explain this by the fact that the whole cracking zone is well protected by this type of repair.

CONCLUSIONS

We wanted to know the resistance of the pipeline to pressure variations in terms of the propagation of the initiated crack, on the one hand, and the interest in a repair, either patch or half shell, on the other. Fig. 16 shows the applications carried out on the pipeline while under internal pressure.

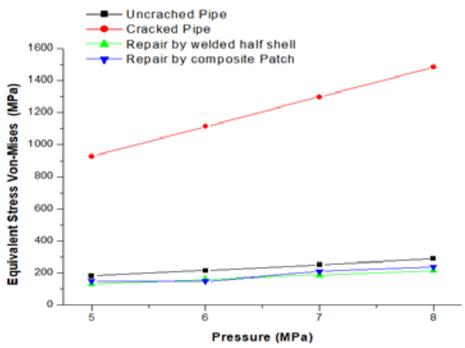

Fig. 16 Von Mises stresses for the four cases studied

Before repair

- The pipeline operates and resists the influence of the internal pressures applied under normal circumstances (5, 6.7 and 8 MPa).
- Because of the presence of the initiated external semi-elliptical crack, we were able to see that the tube has a rather extensive plasticized zone in its proximity. Von Mises stresses rise in direct proportion to the amount of pressure applied.
- The contours of the stress intensity factor produced in mode I demonstrate the influence of the semi-elliptical fracture and the high level at each pressure variation. The first contour just indicates an initiation, but the other five contours clearly show a steady propagation of the fracture, as indicated by the superposition of the curves produced.
- In mode II, the SIF contours increase along the crack until canceling out at the crack tip.
- The value of the stress intensity factor in mode II is very low compared to K_I.

After repair

We were able to stop the fracture from spreading by repairing it with a half-shell or a patch. Fig. 9 (a) and 13 (a) demonstrate the decrease in the extremely high level of Von Mises stress.

The effect of the presence of the crack on the strains is negligible.

- In opening mode (mode I), we can see that the five contours overlap with a symmetrical distribution and that the level of the SIF has decreased significantly.
- In shear mode (mode II), however, the value of the SIF tends to cancel out at the crack's end.
- Half-shell welding repair and composite patch repair (epoxy carbon) are excellent ways for eliminating the damage of semi-elliptical cracks; these repair methods improve pipeline strength for a significant duration extra life.
- Half-shell repair strengthens the pipeline considerably more than composite patch repair, as evidenced by Von Mises stress values (difference of about 20 MPa).

The SIF is related by the crack, which means that the increase and reduction of SIF values are correlated with the presence of the fracture and its geometry (without forgetting the effect of the internal pressure). With fracture propagation, the findings of K_1 rise and decrease (when the crack is reaching the average length the values decrease with the same increase values).

Both forms of repair, particularly repair by the half-shell, have an important influence in the drop in SIF (they have a significant decrease in the values of K_1 and K_2).

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NOMENCLATURE

K stress intensity factor

K_I stress intensity factor in mode I

K_{II} stress intensity factor in mode II

σ_∞ the infinite stress

a the length of the crack

P pressure