NUMERICAL SIMULATION OF LOCALIZED CORRODED STEEL PIPELINES REINFORCED BY COMPOSITE SLEEVE

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Received: 08 April 2020 / Revised: 17 May 2020 / Accepted: 07 June 2020 /

*Abstract***,** In hydrocarbons transmitting by steel pipeline, the protection systems by coating containing bitumen binders and an active cathodic protection (CP) which the potential is maintained to – 850 mV Cu/$CuSO_4$ are to isolate the steel from the corrosive soil environment and to prevent any corrosion risk. Unfortunately, corrosion problems have been developed under certain conditions generating of pitting corrosion. They are preoccupying phenomenon in oil industry and the major threats that can reduce the structural integrity of pipelines transmission system. Study includes a numerical simulation of X60 steel pipeline structure after corrosion localized damage using ANSYS software. The methodology is to consider the structure in three cases: without defects, after an introduction of an elliptical simulated corrosion pits and after repair by multilayer reinforcement based on composite sleeve. Results showed that the stress state variation in each case is different. In the case of corroded structure by a parabolic default the Von Mises Stresses are distributed no uniformly. The default has a maximum stress which can cause a corrosion pitting propagation and requires repair. In the case of corroded structure and reinforced by composite sleeve, the maximum von Mises stress is reduced, it's the same that a non corroded pipe which shows the necessity and effectiveness of structural reinforcement by composite sleeve.

Keywords : localized corrosion, API steel, pitting corrosion, numerical simulations, repair, composite sleeve, multilayer.

1. Introduction

Some operating buried transmission pipeline systems will develop unforeseen surface corrosion. Corrosion phenomenon is accentuated by the soils parameters influence such resistivity, pH, temperature, moisture content and chemical composition of electrolytes contained in soil. X60 carbon steels of GZ1 line pipe in Algeria is done by coated externally and internally steel pipelines which could be buried or overhead. These metallic structures are sensitive to corrosion [1] and failure by cracking or by geometric instability at the slightest imperfection shape (geometrical defects). The main causes of failures are of various kinds. They can occur either by a rupture or a leak. Most they are caused by pitting corrosion or by corrosion cracking. The process of soil corrosion involves many parameters such as soil composition, resistivity… Pipeline structure is protected externally by a bituminous coating whose action is coupled with a cathodic protection system with a minimum specified potential of – 850mV (Cu / $CuSo_4$). Unfortunately, corrosion and cracking problems still can occur in the system under certain conditions. External corrosion pits and cracking phenomena are the main deterioration mechanism under coating failure and cathodic protection (CP) that can reduce the structural integrity of buried gas transmission pipelines. Steel tubes have been exploited for thirty years. They present today several anomalies characterized by the interaction of material with soil environment. Most of these problems do not cause ruptures, but they can produce leaks.

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Most they are caused by pitting corrosion or by corrosion cracking. The process of soil corrosion involves many parameters such as soil composition, resistivity…in complex phenomena. It can be seen in its overall shape as a spontaneous reaction of electron exchange at the metal / environment interface. Their sizing is done by using simplified rules; this approach is generally conservative. The design is usually based on the knowledge of the real or perceived initial state. However, this configuration evolves over time, there is generally an adding of new deformities due to the operation (accidental loads, deformation), but also to the loss of material located in the corroded areas. By taking into account these various damage, generally they led to a loss of bearing capacity.
The maintenance consists in protecting by limiting failures such as corrosion, by reinforcing using a material such as a composite material. For the past ten years, an alternative has been proposed: it is a question of strengthening or repairing metallic structures with composite materials with a polymer matrix bonded externally to defective or degraded structures. Composite materials, in particular based on carbon or glass fibers, due to their specific rigidity, are of great interest for repair
The metallic structures confinement is carried out using envelopes made of composite materials based on glass fibers, carbon or aramid. These envelopes applied to structures improve the confinement of the metal, as well as its ductility and resistance. The different composites offer various elasticity and stiffness modules which can modify the axial and radial behavior of the confined metal. Thus, in order to preserve the charge potential of the structure, it is necessary to reinforce it by strengthening with composite material fibers (glass/ carbon) in the form of one or more layers of composite solutions. They will be investigated in this study as a collage on the metal shell. The research was developed in order to use the composite materials as a layers protection [2 -9].
A Fiber Reinforced Polymer Matrix (FRP) composite made in fiber reinforced polymer / plastic matrix is used in several applications for the construction and renovation of cylindrical elements filled and hollow in the air, marine and underground given their efficiency, performance and availability.
Many developments, practices and products are available in this area, for example: Clock Spring used commercially [10]. In addition, the successful application of fiber-reinforced composites has been illustrated in the rehabilitation of corroded pipelines using hybrid repair [11], the rehabilitation of tubular steel structures with CFRP aimed at assessing the possibility of rehabilitating members bending in tubular steel with a focus on subsea applications [12].
We are interested in this project to study the behavior of the X60 steel metallic structure of GZ1 pipelines under stresses by soils leading to pitting corrosion and repairs by bonding of sleeves based on composite materials. The objective of numerical study is to show the effectiveness of repair by composite materials bonding in numerical modeling study without defect, with defect, and with defect repaired by composite bonding using Ansys software. This study will be conducted on Clock Spring repair methods for the GZ1 API 5L X60 steel line operated by the Sonatrach company in Algeria.

2. Materials and methods

2.1. Study material

The chemical composition of the study material was made by spectrophometric analysis type ``SPECTRO Rp 212″ available at the ALPHAPIPE society in Annaba plant spiral tubes. (Table1)
It will be noted that the sulfur content is very low compared to the contents encountered in the grades of current transport tubes. This results in a low inclusion content and therefore good ductility. In addition, the presence of very small amount of aluminum is revealed for deoxidation.
The results of the tensile test for X60 steel are given in table 2.
The characteristics of materials (Glass/epoxy composite, adhesive and steel) are given in table 3

Table 1. Chemical composition of X60 pipeline steel [13].

C	Si	Mn	P	S	Cr	Ni	Mo
0.213	0.380	1.35	0.015	0.016	0.025	0.024	0.013
Al	Co	Cu	Nb	Ti	(S+P)	Ceq	Fe
0.067	0.007	0.029	0.078	0.003	0.031	0.45	97.8

Table 1. Tensile stress [13].

Tests number	Re (MPa)	Rm (MPa)	A %	Z %
1	410	557	32	49
2	413	569	30	53
3	417	578	33.3	55
Average	413.33	568	31.76	52.33

Re - Elastic limit
Rm - tensile strength
A - Total Elongation
Z – striction

Table 3: *characteristics of materials (composite, adhesive and steel) [3]*

	Materials	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{13}	ν_{23}	G_1 (GPa)	G_2 (GPa)	G_3 (GPa)
Clock spring	Glass/epoxy	160	25	25	0.21	0.21	0.21	7.5	5.5	5.5
adhesive	FM73	255			0.32					
Pipe	Steel X60	210			0.30					

E- Young modulus

2.2. B31G model

ASME B31G [14] is a code intended to evaluate the breaking strength residual of a corroded pipe. It constitutes an additive to ASME B31 used for the tubes under pressure. The entry parameters comprise the external diameter (Dext), the thickness (t), the necessary minimal elastic limit, the maximum operating pressure, the longitudinal maximum extension of corrosion (2c) and the depth of the defect (a).

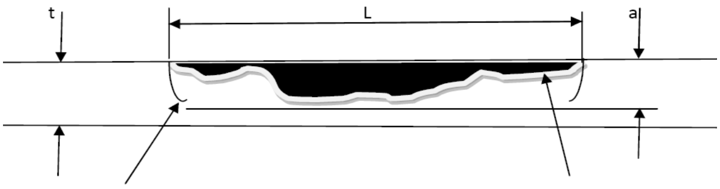

Figure 1 Long defect of corrosion projected according to a rectangular form

The rupture equation of the corroded tubes is established starting from the experimental data and is expressed from the two following conditions:

- Firstly, the maximum total circumferential constraint cannot exceed the elastic limit of material.
- Secondly, a defect of corrosion runs is compared to its projection according to a parabolic form and a long defect of corrosion is projected according to a rectangular form.

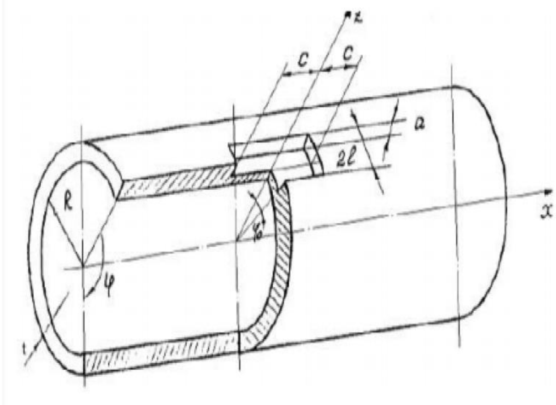

Figure 2: Representation of a corrosion defect on the tube

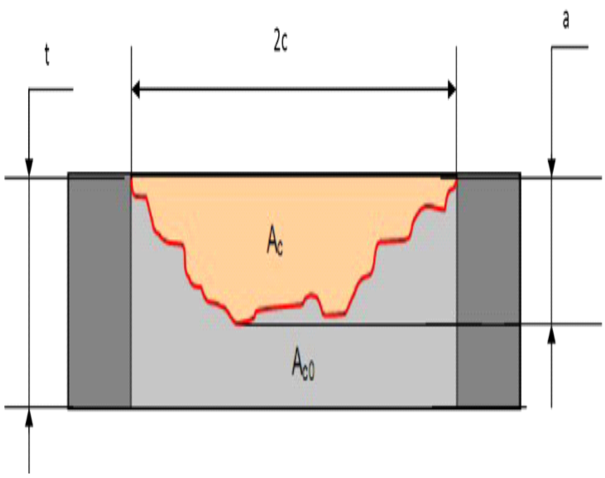

Figure 3: Front longitudinal of a corrosion defect

3. Numerical simulation

Industrial problems such natural gas pipeline transmitting are usually modeled by partial differential equations. These equations are hard to be solved; this leads us to the use numerical approximation methods. The finite element method has now becomes one of the most common numerical methods for solving these equations. Its efficiency has been proved in several areas of science including solid mechanics, fluid mechanics, heat, electricity and electromagnetism. Pipeline tubes are thin ones; this is due to the fact that the thickness of the pipe is less than $t/D_{ext} \leq 0.05$. Samples of the considered structure are: (D_{ext} = 1016, t = 12.7mm) in the case of GZ1 line in Algeria where D_{ext} is the external diameter of tube and T is the thickness.

Numerical simulation is a validation step close to possible data and experimental conditions. In the context of our study, the sample structure is essentially composed of a cylindrical specimen (single hull curvature) under elastic behavior patterns or elastoplastic [15]. The simulation combines geometric representation, a mechanical model, a model of equipment behavior and representation of external actions (boundary conditions). [15] We summarize below the assumptions for each of these characteristic representations of materials in order to showing the different situation and cases of the corroded pipe.

We considered initially the pipe structure without defect by varying the thickness and diameter and in a second step the structure comprising a parabolic failure such as loss of corrosion metal and we will finish this simulation by considering the structure repaired by composite sleeve approaching the industrial context. Numerical modeling was done by ANSYS software. The simulation combines geometric representation, a mechanical model, a model material behavior and representation of external actions (boundary conditions)

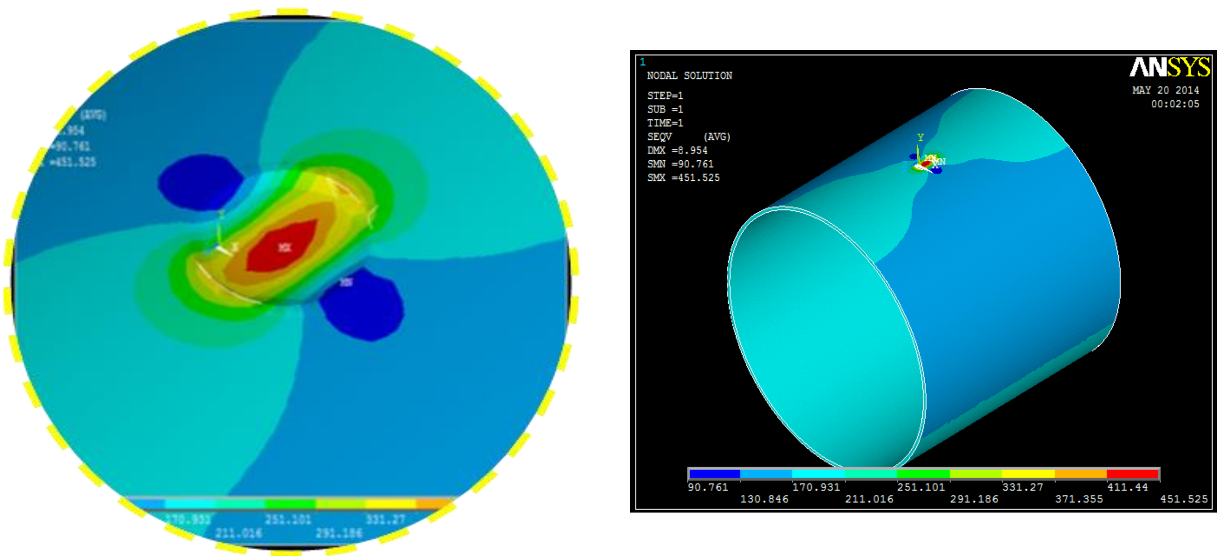

Figure 4 Tube under internal pressure have a parabolic default p_i *= 5 MPa, damage rate 50%*

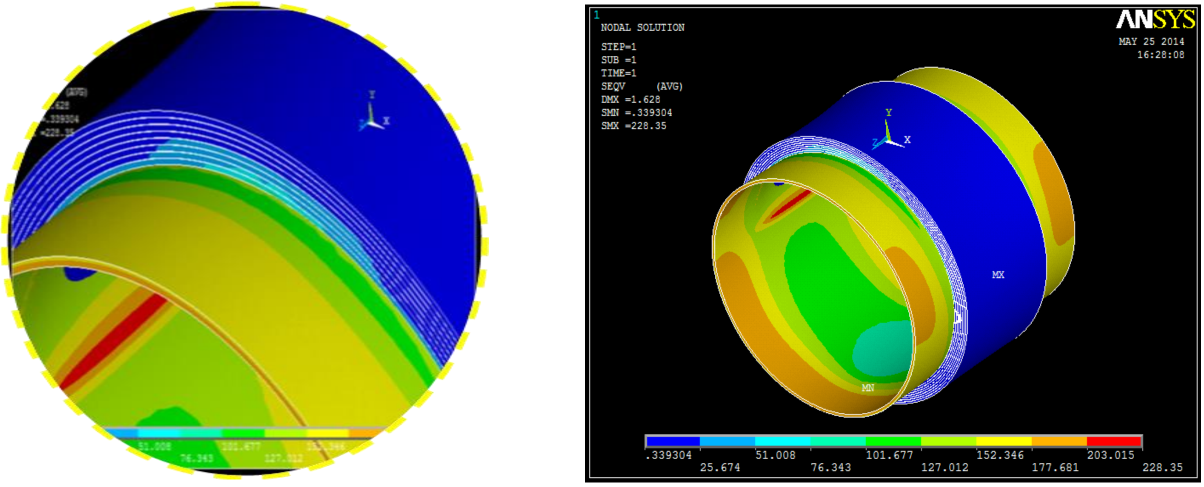

Figure 5 Tube under internal pressure have a parabolic default repaired by 8 filled composite layers p_i = 5 MPa, damage rate 50%

The results of the simulation showed that the stress state structure is changed by considering the pipe without corrosion defect, with parabolic corrosion defect and repaired by composite sleeve type clock spring.

The distribution of the VON MISES equivalent constraints is showed in figure 6 and figure 7

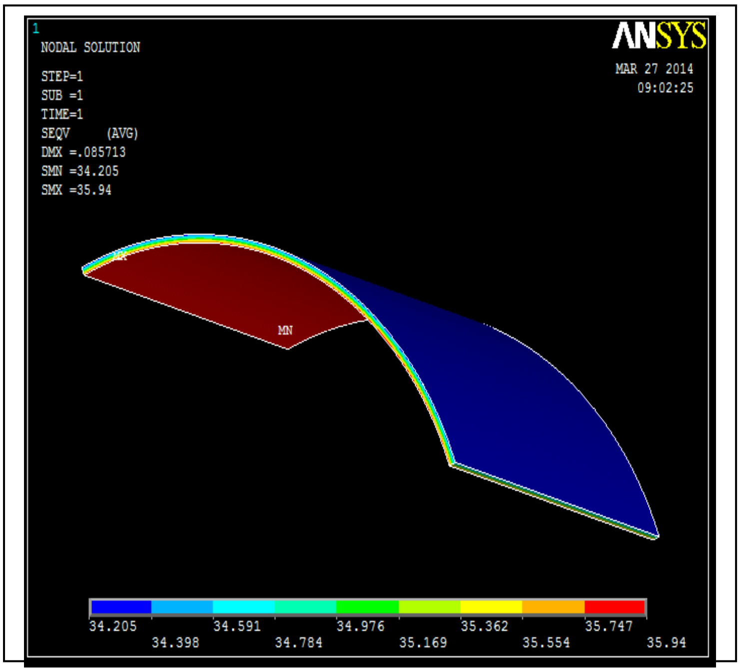

Figure 6: Tube under internal pressure (Pi)
(API grade steel 5L X60, Pi = 1 MPa, D_ext = 1016mm, t = 12.7mm).

Dext – External diameter

t- thickness

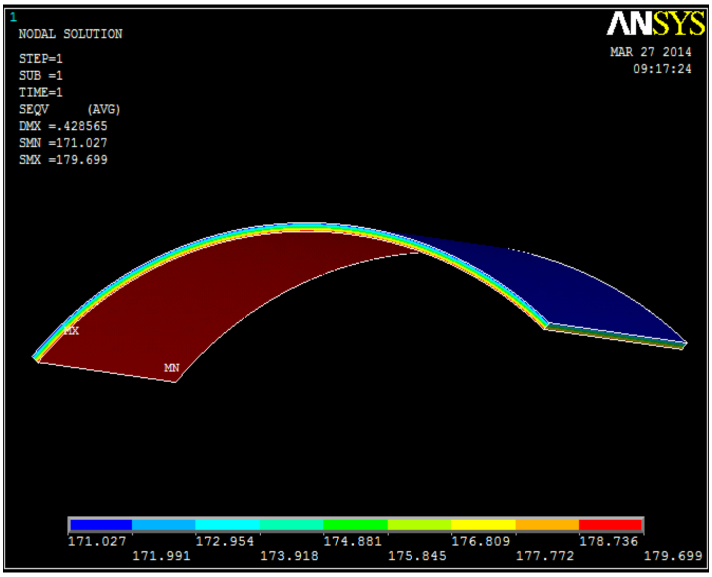

Figure 7: Tube under internal pressure (Pi)
(API grade steel 5L X60, Pi = 5 MPa, D_ext = 1016mm, t = 12.7mm).

4. Results and discussions

Study in this project is to consider the mechanical behavior of the metallic structure of pipelines under stress from soil leading to corrosion failures (pitting corrosion) and repairs bonding materials based on sleeves composites.

4.1 Pitting corrosion

API steels are protected from the external soil corrosion by a bituminous coating whose action is coupled with a cathodic protection system (minimum potential specified -850 mV versus (Cu / $CuSO_4$), which aims to maintain steel in its protection field and thus, to avoid any risk of corrosion during a possible rupture of the coating. Unfortunately, corrosion problems have appeared on the steel surfaces under certain conditions as a result of interactions of pipes material with the soil environment, mainly in the localized corrosion pitting form, pipeline perforation, coating failure, cracking and biocorrosion... These failings occurred in consequence of bare steel interaction in the aggressive area soil like soil clay or saline underground waters subsoil. Corrosion steels phenomenon in buried structures such as a line gas transmission pipelines is the main problems in oil industry and a complex phenomenon of damage. It depends of the particular site and several parameters such as soil resistivity, pH, soil composition... We have analyzed the resistance of tubes in an ideal situation where there are not defects.

4.2 Pipe repair by composite material bonding

In this project, steel repair by composite material bonding after failure by localized corrosion (pitting corrosion) is considered by numerical simulation, where showed it interest in the interpretation of the results and the possibility of obtaining inaccessible experimentation information. It has been shown in the second step, the study of damage corroded tubes for parabolic default rates. The damage rate was 70%. We note that the Von Mises stresses are distributed non- uniformly corroded parabolically generator tube, and the default has the maximum stress that will cause a failure after a certain time which requires repair. In the third step, we studied the same tube corroded to second stage except that it is a reinforced composite sleeve. In this simulation we have saw that the maximum von Mises stress is reduced almost 3 times a corroded pipe as shown in Figures 5. Results showed that the maximum

von Mises stress for a corroded pipe and reinforced a sleeve made of composite material is almost maximum stress a flawless pipe which shows the necessity and effectiveness of strengthening the structure damaged by sleeve-based on composite material.
Figure 4 shows a cylindrical tube under internal pressure parabolic defect that we can see the effect of the internal pressure of the equivalent stress. Equivalent constraints according to Von Mises are distributed non- uniformly on the generator tube parabolically corroded, and the defect has the maximum stress that will cause failure after a time which requires repair.
In figure 5, results showed that the maximum von Mises stress is decreased almost three times in a corroded pipe repaired and filled and almost represents the maximum stress a flawless tube which shows the need and the efficiency of defect filling in the building structure by the sleeve composite material . Figure 5 also shown that stress concentration state is distributed homogeneously on the defect surface when it is filled. This shows the need for defect repair before filling composite bonding to obtain a better repair. These results were obtained by considering the repair by bonding composite sleeve type clock spring. We have not considered other types of bonding where the results may be different.

5. Conclusion

Metallic structures such as steel pipelines transporting hydrocarbons are solicited by localized corrosion failures. The simulation study has shown that the structure containing defects is characterized by a stress concentration at the site of the defect, which can cause the spread of this anomaly and the collapse of the structure.
The results showed that the structure containing defects is a structure which is exposed to risks of deterioration. This shows the need for repair
The maximum von Mises stress is decreased almost three times in a corroded pipe repaired and filled and almost represents the maximum stress a flawless tube which shows the need and the efficiency of defect filling in the building structure by the sleeve composite material . Stress concentration state is distributed homogeneously on the defect surface when it is filled. The results of the reinforcement sleeve based on composite material have shown that the stress reaches almost the constraint of a flawless tube.
The results of the reinforcement by a sleeve based on composite material have shown that the stress almost reaches the stress of a defect-free tube and the repair results are better when the defect is filled before bonding. The results of the reinforcement by a sleeve based on composite material have shown that the stress almost reaches the stress of a defect-free tube and the repair results are better when the defect is filled before bonding.
Repair by bonding of composite was chosen by the STT from Sonatrach Society in Algeria for the pipeline structures repair . Although there is currently a lot of interest in this technique due to the lighter weight of the structures associated with it, special attention must be paid to the durability of bonded assemblies under service conditions. The presence of interfaces at various scales brings into play specific phenomena, which are particularly sensitive to the environment and the effects of synergy. The interest of specific preparation and implementation processes for this application has been highlighted, as well as physical characterizations allowing evaluating the properties of the adhesive. These studies made it possible to guarantee the performance and durability of the assemblies.
The effect of various types of stress such as mechanical stresses and environmental stresses not only modifies the behavior of the adhesive but also acts on the interfacial interactions and the adhesion forces. These stresses are factors of the decrease in the mechanical resistance of the joints, the loss of the adhesion function and the decrease of the service life of the bonded joints.
Finally, from our simulation results, we can conclude that repair by bonding of composite is very effective and promising for the repair of metal structures.
In perspective, it would be desirable to apply this repair method by looking for suitable composite materials while minimizing the number of repair turns where the bonded assembly would be more resistant, the environmental stresses would be low and the repair time would be reduced.

Acknowledgements

The authors are very grateful to the Algerian gas transport TRC/DRC – Sonatrach Arzew for their great help to make a part of this work to be done. They also appreciate financial support from the Algerian Ministry of higher education and scientific laboratory research from Tlemcen university

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