Optimization of the geometrical parameters of bonded composite wrap for repairing cracked pipelines

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ABSTRACT. In this study the finite element method is used to analyze the performances of bonded composite wrap repair of cracked steel pipelines. Parametric analysis was performed in order to highlight the effects of the geometrical properties on the repair efficiency. The experimental design method is used to explore the effects of wrap dimensions (length, angle and thickness) in order to optimize the repair process. We showed in using the MOODE.5 software the most dominant geometrical parameters on stress intensity factor at the crack front which to determine the most important parameters on the repair efficiency. This optimization can help the composite wrap designers to improve the repair performance and rehabilitation.

KEYWORDS. Fracture mechanics; Crack; Composite; Wrap; Pipelines.

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INTRODUCTION

The oil and gas are transported by steel pipelines in industry better than the storage tanks. The operating conditions are in subjected to hard environments and extreme loading conditions. Mechanical damages are common in operating pipelines. They are damage in the coating, erosion and corrosion which can lead principal problem met in industry to internal and external crack in the structure of the pipeline. According to the gravity of the problem, the harmful effects are the pressure bearing capability in the pipeline and they can reduce his lifespan or a failure of the structure [1-5]. The best means of reparation of canalization is the bonded composite wrap because he is installed during the continuity flow of the fluid and there is not hot work in order to avoid the risk of explosion. The use of the composite wrap as an alternative of the cracked replacement pipe often saves economical resources to immediately pay behind costs of repair [6-10]. After the realization of 2 to 65 composite wrap repairs on pipelines more than 300 mm of outer diameter can save 15.000 to 780.000 m^3 of natural gas by year. In choosing the composite wrap, they saved 4 .106 m^3 of gas during 5 years [11].

A study conducted by the US Department of Transportation showed repair costs can be reduced by 24% by using composite repair instead of welded steel sleeves. When compared to the replacement of the whole defective pipe section, the cost can be further reduced to approximately 73% [12]. The strength of the repair is governed by the thickness of composite wrap and the tensile stress at each layer of the wrap, where effective stress transfer initiates once plastic flow occurs in the repaired steel pipe [13,14]. Murad et al [15] developed an integrated structural health monitoring approach for composite-based pipeline repair. However, the cumbersome process of installing electrical strain gauges on the steel pipe prior to the application of the composite repair greatly limits its adoption in offshore subsea application.

Numerical methods such as finite element method (FEM) have grown considerably in recent years. Several authors have used this method to analyze the performance of pipe repair by a composite patch [16-20]. The majority of these authors have used the linear mechanics of fracture approach to evaluate the reduction of stress intensity around the crack front by the composite wrap. Benyahia et al [18] calculated the stress intensity factor (SIF) at the front of repaired crack with bonded composite wrap in pipe subjected to internal pressure. They showed that the composite wrap repair leads to a significant reduction of the SIF which improves the service life of the cracked pipe. The same conclusions were made by Bezzerrouki et al [19] who studied the performances of bonded composite wrap on pipes subjected to traction. However, for pipe subjected to bending moment the repair efficiency is less significant according to Achour et al [20].

A finite element study of cracked steel circular tube repaired by fiber reinforced polymer composite (FRPC) patching is executed by Lam et al [21]. It was shown that the mode I stress intensity factor (KI) of cracked steel members was found to be reduced with the application of FRPC patching. Using the KI and Paris equation [22], the fatigue life of the cracked steel member was increased by 22 times with the application of FRPC patching. The various works conducted have showed that application of FRPC to reinforce structural element is a viable option. Experimental testing can be used as a means of determining the effectiveness of the repair or reinforcement [23,24]. The use of numerical modelling can be a more cost effective solution where accurate results have been shown to be attainable through numerous previous studies [25,26].

The design of bonded FRPC wrap for repairing damaged pipe line has not been studied enough in the literature. The use of fiber-reinforced polymer composite as a load bearing sleeve has emerged as a promising means of pipeline rehabilitation due to advantages such as high specific strength, high corrosion resistance, lightweight, do not require welding and are simple to install [27].

Erdogan et al. [28,29] studied on the cracked panels using an analytical formulation for the fracture parameters such as stress intensity factor. Other closed-form expressions for SIFs are presented by Zahoor [30], Sanders [31] and Forman [32] for cracked cylindrical pipes. Zárate et al. [33] presented a framework to update and predict crack length as a function of the number of cycles in structural elements subjected to fatigue.

In all previous researches of bonded composite repair of damaged pipe, the optimization of the repair parameters was not made. The objective of this work is to optimize the repair parameters in the technique of repair of cracked pipeline with composite wrap. To achieve this objective, a finite element study is used to analyze the performance of cracks repaired with composite patches by calculating the crack stress intensity factors in elastic behaviour. The effect of the geometrical properties on the reduction of the stress intensity factor at the crack tip is also analyzed.

The obtained results are analyzed by the methodology of the experimental design to develop a constitutive mathematical model which controls the stress intensity factor as a function of the combination of three geometrical parameters of bonded FRPC wrap: length, angle and thickness.

This experimental design method was applied to optimize the FRPC wrap size and to find the most influencing dimension on the repair efficiency.

MODEL DESCRIPTION AND MECHANICAL PROPERTIES

Consider material alloy often used in gas pipelines, API 5L grade X65 containing a longitudinal external semi-elliptical crack of length (2c = 15.4 mm) and depth (a = 2.8 mm), he is repaired with a FRPC wrap, the fibres are all oriented at 0° stuck around the entire circumference of the pipeline, the model is shown in Fig. 1. The geometrical and mechanical characteristics of the pipeline, the composite wrap and the adhesive are shown in Tab. 1 and 2 respectively.

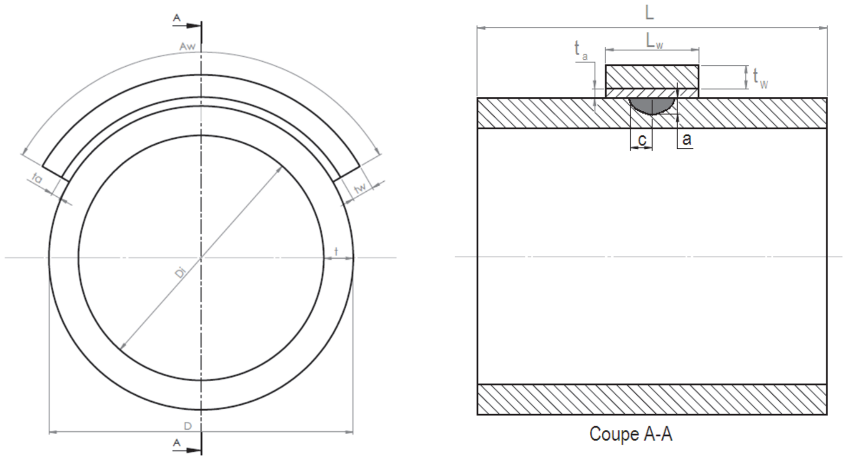

Figure 1: Repair by composite wrap of a semi-elliptical crack in a pressurized cylinder.

Symbol	Value	Description
L	9000	Pipeline length (mm)
D	864	Pipeline outside diameter (mm)
D_i	847.44	Pipeline inside diameter (mm)
t	8.28	Pipeline wall thickness (mm)
a	2.8	Crack depth (mm)
C	7.7	Half crack length (mm)
Lw	[100-350 -600]	Composite wrap length (mm)
tw	[6-18-30]	Composite wrap thickness (mm)
Aw	[30- 195 -360]	Composite wrap recovery angle(°)
ta	0.1	Adhesive thickness (mm)

Table 1: Dimensions of typical repair of pipeline.

Property	Material			Description
	Steel	Glass/Epoxy	Adhesive	
E1	209000	159000	2400	Young's modulus in X direction (MPa)
E_2		25400		Young's modulus in Y direction (MPa)
E_3		25400		Young's modulus in Z direction (MPa)
ν_{12}	0.3	0.28	0.3	Poisson's Ratio in X-Y plan
ν_{13}		0.28		Poisson's Ratio in X-Z plan
ν_{23}		0.15		Poisson's Ratio in Y-Z plan
G_{12}		7190		Shear modulus in X-Y plan (MPa)
G_{13}		5430		Shear modulus in X-Z plan (MPa)
G_{23}		5430		Shear modulus in Y-Z plan (MPa)
σ_y	456000			Yield stress (MPa)

Table 2: Mechanical proprieties of materials.

NUMERICAL MODELING AND BOUNDARY CONDITION

The pipeline is modelled in the commercial finite element software, Abaqus [34]. Continuum elements with eight nodes and reduced integration (C3D8R in Abaqus) were used throughout the model. The total number of elements generated for the symmetrical model was 686950. The mesh is refined at the crack front, composite wrap and adhesive layer.

The pipeline is subjected to internal compression $P_i = 0.57$ MPa with distributed uniform stress. The model is shown in Fig. 2.

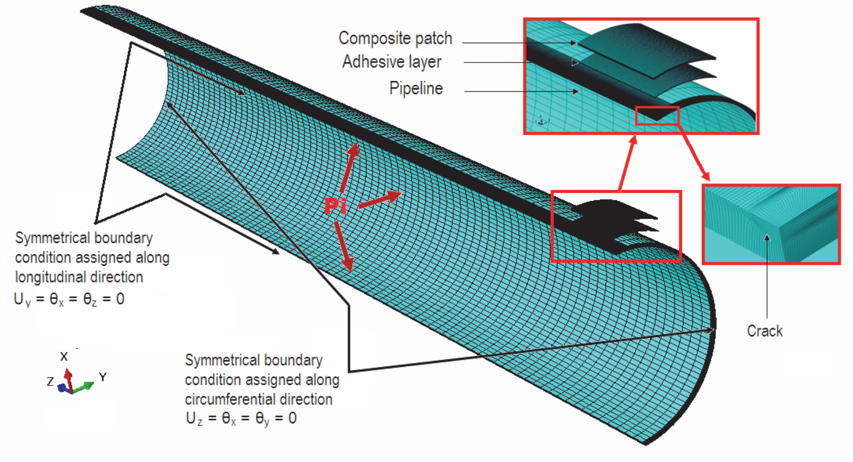

Figure 2: Finite element model of repaired crack by composite wrap.

EXPERIMENTAL DESIGN APPROACH

The experimental design is necessary to have relevant information, establish a relationship between the input variables, which are the geometrical parameters (the length, the thickness and especially the width of the recovery angle of the composite wrap bonded) and the output variables is the evolution of the mode I stress intensity factor (K_I). In order to determination the optimum patch dimensions. Each parameter was tested at three different levels: The length of wrap (100-350-600) thickness of wrap (6-18-30) and the recovery angle (30-195-360).

The responses (stress intensity factor) were calculated using the finite element method. The experimental design matrix of the experiments is given by MODDE 5.0 (Modelling and Design) software [35,36] is presented in Tab. 3.

We have adopted a complete experimental design of three factors at two levels; the mode of the experimenter is quadratic and has the following form:

$$y = a_0 + \sum_{i=1}^{3} a_i x_i + \sum_{1 \le i \le j \le 3} a_{ij} x_i x_j + \sum_{i=1}^{3} a_{ii} x_i^2 + e \qquad (1)$$

where i, j vary from 1 to the number of process variables 3, y is the response of the process (stress intensity factor); The coefficient a_0 is the means of answers for the whole experiment; The coefficient a_i represents the effect of the variable x_i and a_{ij} are the regression coefficients that represent the effects of the interactions of the variables x_i x_j and a_i are the regression coefficients that represent the effects of the interactions of the variable x_i x_i and e is the experimental error.

The polynomial model proposed by MODDE 5.0 describe the variations of the response function (stress intensity factor) K_I to the factors L_w, t_w and A_w is of the following form:

$$\begin{aligned} K_I = a_0 + a_1 L_w + a_2 t_w + a_3 A_w + a_{12} L_w t_w + a_{13} L_w A_w + a_{23} t_w A_w \\ + \mathrm{a}_{11} \mathrm{L}_w^2 + \mathrm{a}_{22} \mathrm{t}_w^2 + \mathrm{a}_{33} \mathrm{A}_w^2 \end{aligned} \qquad (2)$$

The experimental plans used in this study are a complete quadratic plan to say that we deal with a mathematical model of the second degree. Tab. 4 presents the coefficients of the various parameters and their interactions.

The mathematical model proposed by MODDE 5.0 is expressed as follows:

$$\begin{aligned} K_I &= 21.3496 - 4.71944 L_w - 14.7872 t_w - 7.66384 A_w - 3.41241 L_w t_w \\ &+ 1.43191 L_w A_w + 3.47017 t_w A_w + 3.794 L_w^2 + 3.06383 t_w^2 + 6.11351 A_w^2 \end{aligned} \tag{3}$$

Exp. no	Lw (mm)	tw (mm)	Aw (°)	K$_I$ (MPa√m)
1	100	6	30	60.65
2	350	6	30	54.29
3	600	6	30	55.07
4	100	18	30	50.641
5	350	18	30	40.04
6	600	18	30	35.77
7	100	30	30	30.19
8	350	30	30	19.65
9	600	30	30	10.988
10	100	6	195	41.61
11	350	6	195	42.2
12	600	6	195	45.92
13	100	18	195	30
14	350	18	195	16.95
15	600	18	195	16.33
16	100	30	195	21.83
17	350	30	195	10.09
18	600	30	195	8.363
19	100	6	360	39.22
20	350	6	360	35.81
21	600	6	360	37.48
22	100	18	360	27.42
23	350	18	360	16.46
24	600	18	360	17.98
25	100	30	360	22.27
26	350	30	360	11.72
27	600	30	360	10.98

Table 3: The conducted table experiments given by the experimental design.

K$_I$	Coeff. SC	Std. Err.	P	Conf. int(±)
Constant	21.3496	1.77809	9.97244e-010	3.75146
Lw	-4.71944	0.823094	2.43432e-005	1.73659
tw	-14.7872	0.823094	1.71477e-012	1.73659
Aw	-7.66384	0.823094	4.36222e-008	1.73659
Lw*Lw	3.794	1.42564	0.0164509	3.00786
tw*tw	3.06383	1.42564	0.0463223	3.00786
Aw*Aw	6.11351	1.42564	0.000497399	3.00786
Lw*tw	-3.41241	1.00808	0.00351972	2.12688
Lw*Aw	1.43191	1.00808	0.173562	2.12688
tw*Aw	3.47017	1.00808	0.00310919	2.12688
N = 27	Q2 =0.919		Cond. no. =5.2299	
DF = 17	R2 =0.967		Y-miss =0	

Table 4: SIF K$_I$ coefficients list.

RESULTS

From the graphical analysis it is possible to determine the influence of each factor on the response. The stress intensity factor responses are predicted by MODDE 5.0.

Effect of composite wrap thickness on SIF

The influence of the composite wrap thickness on the stress intensity factor is summarized in Fig. 3. The results show a strong influence of the composite wrap thickness on the stress intensity factor, the higher the composite wrap thickness, the lower the stress intensity factor. A difference of about 400% in the stress intensity factor between the two composite wrap thicknesses (6 and 30) is observed.

The analysis of this figure shows that an increase in the thickness of the wrap causes a decrease in the stress intensity factor. These results are in agreement with those of Bezzerrouki et al [19]. If thicker wrap is used, the stress level at crack front decreases. This behaviour can be explained by the fact that the bonded composite wrap significantly reduces the mechanical energy at the crack front which attenuates the crack growth rate. This reduction is more significant when the wrap thickness increases.

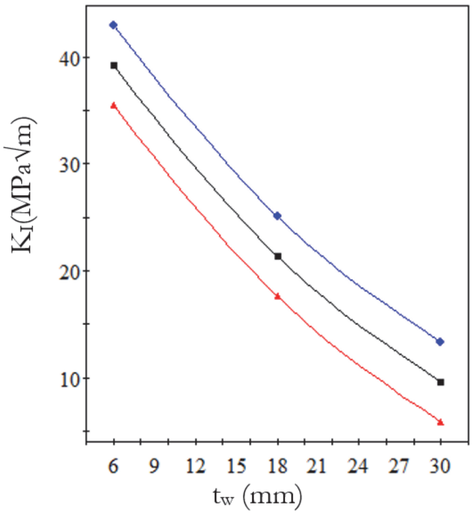

Figure 3: SIF vs composite wrap thickness.

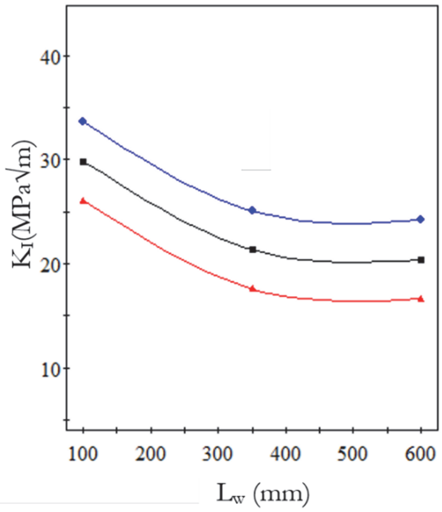

Figure 4: SIF vs composite wrap length.

Effect of composite wrap length on SIF

Fig. 4 illustrates the influence of the composite wrap length on the stress intensity factor; we observe that an increase of this length leads to a decrease in the stress intensity factor. Until reaching a minimum value of 21 MPa.m$^{1/2}$, which corresponds to a value of L_w = 350 mm, beyond this value the composite wrap length has no influence on the response K_I. About the wrap length effects, it can be noted that the composite wrap length give weak stress intensity factors and consequently best repair efficiency. This is because with longer composite wrap the bonded area increases and the stress transfer from the pipe toward the composite wrap will be more significant.

Effect of composite wrap recovery angle on SIF

Fig. 5 illustrates the effect of the composite wrap recovery angle of the stress intensity factor by analyzing this curve it can be said that the increase in the angle generates a considerable decrease in the stress intensity factor. Indeed, an increase of 300° in the composite wrap recovery angle leads to a 75% decrease in the stress intensity factor. This effect is less marked for a composite wrap recovery angle of 233°.

Interaction effect of different parameters on SIF

In this analysis step we expand our comments taking into account this time an interaction between two factors while keeping the other two constant this decision allows us to visualize the variation of the stress intensity factor by a graph in three dimensions in Fig. 6.

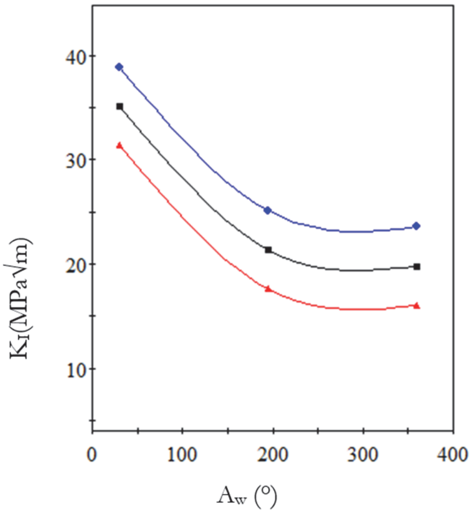

Figure 5: SIF vs composite wrap recovery angle.

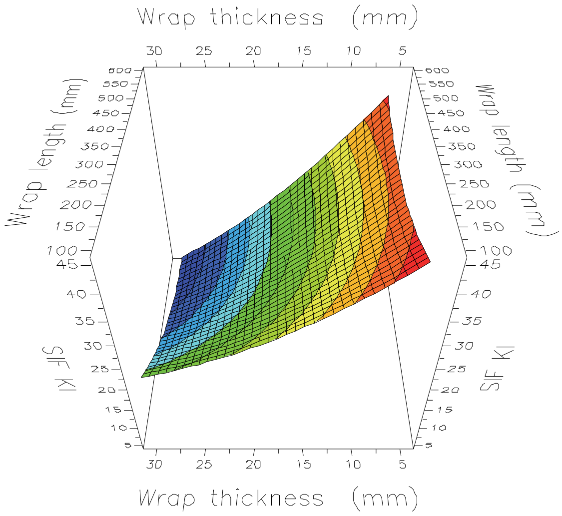

Figure 6: Surface plot of SIF vs thickness and length of wrap.

Fig. 7 is the projection of the surface 6 on the plane (iso-reponse), which presents the effect of the combination of the two factors for a constant value of wrap recovery angle A_w = 195°, the composite wrap length and the composite wrap thickness on the stress intensity factor. In this case combination, the stress intensity factor is optimal when these two factors take maximum values.

Fig. 8 shows the effect of the combination of the two factors, the composite wrap length and the composite wrap recovery angle on the stress intensity factor. The results obtained show that the more these factors increase, more the stress intensity factor decreases, for a composite wrap length value between 400 and 600 mm, and for composite wrap recovery angle between 125° and 330 °. We conclude this analysis that to have a better reparation, it is necessary to have a maximum value of the composite wrap length and a value of the composite wrap recovery angle equal to 233°.

Fig. 9 illustrates the variation of the stress intensity factor as a function of the thickness composite wrap and the recovery angle. Following this combination, it is found that the increase of these two factors causes a decrease in the stress intensity factor. Concludes that to have a significant life time, composite wrap thickness maximized and the composite wrap recovery angle must be equal to 233°.

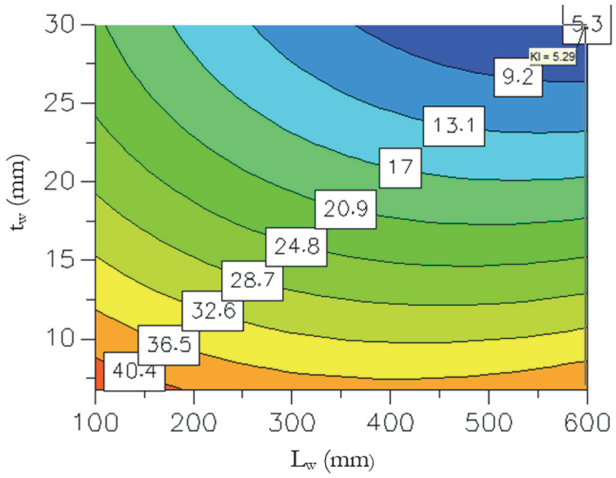

Figure 7: Contour plot of SIF for wrap recovery angle constant A_w = 195°.

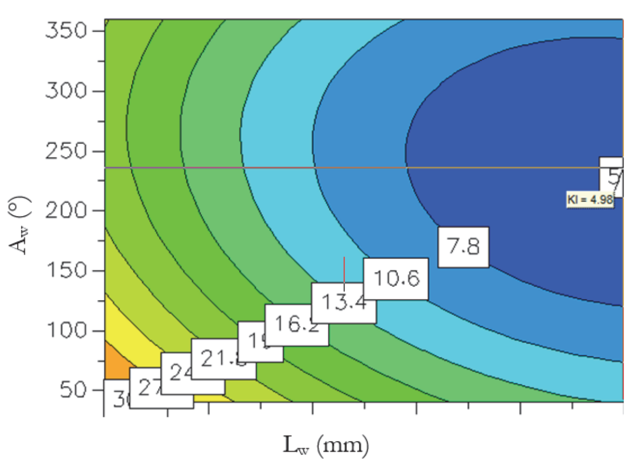

Figure 8: Contour plot of SIF for wrap thickness constant t_w = 30 mm.

By introducing the results into the MODDE 5.0 software to examine the different effects, the results obtained are given in Fig. 10. This diagram shows the effects of all combinations of the factors performed (linear, crossed and quadratic). In

descending order of their importance in absolute value. By analyzing these results, we can say that the dominant factors on stress intensity factor are in the following order:
1- Composite wrap thickness.
2- Composite wrap recovery angle.
3- Composite wrap length.

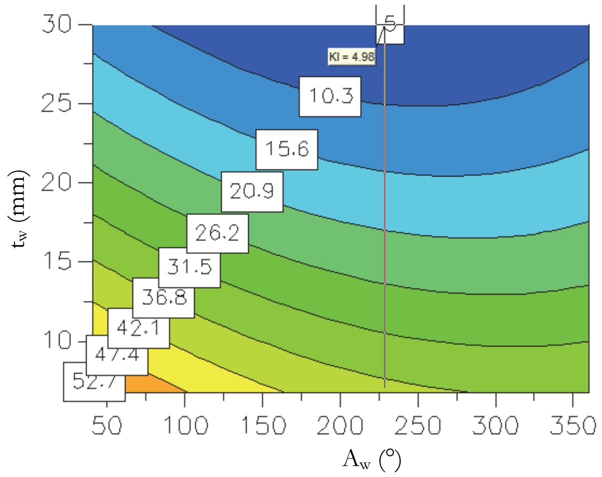

Figure 9: Contour plot of SIF for wrap length constant L_w = 600 mm.

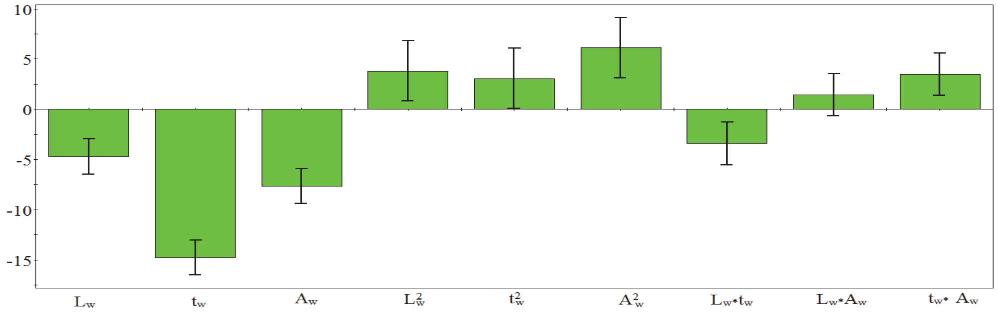

Figure 10: Effects of the different parameters on the stress intensity factor K_I.

Optimal composite wrap dimension

From the optimization software, we can deduce the minimal value of the SIF which is equal to 4.9777 MPa.m$^{1/2}$. This value gives the better repair efficiency (Tab. 5). It is obtained from the following dimension of the composite wrap: length L_w=599.413 mm, thickness t_w=29.9999 mm and recovery angle A_w = 233.967°.

Lw	tw	Aw	KI
550	30	228.594	5.1817
559.262	29.9031	275.268	5.5471
588.105	29.9992	236.796	4.999
566.146	29.5898	239.624	5.4477
599.413	29.9999	233.967	4.9777
556.166	29.8859	238.203	5.2314
600	30	228	4.9805
566.146	29.5898	239.624	5.4477

Table 5: Optimal FRPC wrap sizes.

The validity of the developed model can also be obtained from the Fig. 11 which presents the relation between the values computed numerically and predicted from the proposed model. This curve indicates that the mathematical model developed shows a good agreement between the calculated and estimated values of the responses.

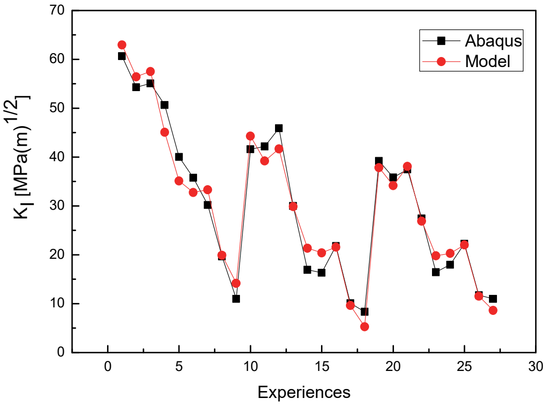

Figure 11: Comparison between the SIF of different program execution and those obtained by mathematical model.

DISCUSSION

Bonded composite repair of cracked pipeline is an efficient technique to increases the lifespan of damaged pipe. The load transfer between the cracked pipe and the composite wrap can attenuate the stress intensity around the front of the repaired crack which leads to the improvement of the fatigue life of the pipeline [37]. It was shown by Benyahia et al [18] in this study that the reduction of the stress intensity by the composite wrap repair is very significant at the external position of the crack compared to the internal crack position. The main disadvantage of the technique of bonded composite repair in pipe is the impossibility to bond double-sided composite wrap in order to equilibrate the stress transfer between the internal and external positions of the cracks [20]. To increase the repair efficiency, it is important to optimize the repair parameters since the stress intensity around the crack depends on all these parameters. The optimization of the mechanical properties of the adhesive and the composite patch can improve the repair and reinforcement performances and durability significantly. This optimization must equilibrate between the reduction in the stress intensity at the repaired defect and the reduction in the risk of adhesive layer failure [19].

The obtained results showed that the wrap length has a significant effect on the repair efficiency, the maximization of this parameter is essential to increase the repair performance. It was also shown that the wrap thickness must be also maximized to improve the repair efficiency. These results are in concordance with those of Achour et al [20]. These authors studied the performances of bonded composite wrap of pipeline subjected to bending. They showed that the increase of the plies number of the composite wrap reduces significantly the stress intensity factor at the crack front. The relative reduction of the SIF is about 30% when the plies number varies between 4 and 14 [20]. These results allow us to confirm that the choice of thicker wraps makes it possible to increase significantly their performances. The optimum of the recovery angle is 233° representing 65% if the global recovery. This is specific for pipe repair because in plate repair the total recovery is the optimum [21].

CONCLUSION

The objective of our study is to highlight the performance of the fibre-reinforced polymer composite wrap repair technique in a pipeline subjected to internal pressure. The analysis of the effect of various geometrical parameters of wrap on the repair efficiency has been studied numerically. The analysis of the influence of these parameters was performed by the method of experimental design. Consequently, the following conclusions can be deduced:

- The bonded FRPC wrap repair improves the lifespan of cracked pipe but the improvement rate strongly depends on the geometrical properties of the FRPC wrap.
- The increasing of the wrap thickness leads to a considerable decrease of the SIF at the crack tip.

- The thickness has the most significant effect on the repair efficiency.
- An increase in the length of the wrap causes the decrease in the SIF of the longitudinal crack; the use of a longer wrap in the axial direction is therefore beneficial for repaired structure.
-In addition, increasing the recovery angle of the wrap on the outside circumference of the pipeline reduces the SIF at the crack front. But we take into account the geometrical design limits of the FRPC wrap for a recovery angle 65% (233°) to have an optimum in reducing the stress concentration at the crack front.
- Optimization sizes reduce the use of the composite material with a gain of 35%.
- The non patched surface absorbs the energy around the crack front leading to a stress relaxation at this front.

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