Prediction and optimization of parameters influence the repair of pipelines using composite patches.

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ABSTRACT :

This work presents an in-depth study aimed at predicting and optimizing key parameters affecting the efficiency of oil pipeline repair using composite materials. Pipelines, subjected to severe operating conditions, can suffer damage such as corrosion or cracks, making rapid and effective repair necessary. The use of composite material repair has emerged as an economical, durable, and minimally intrusive solution.

The study combines numerical modeling and optimization techniques to analyze the influence of the main parameters on the mechanical performance of the repaired system. These parameters include:

The thickness of the composite patch and the fiber orientation angle.

The results show that the thickness and orientation of the fibers play a decisive role in the mechanical strength and reduction of stresses around the defect. Finite element analysis (FEA) tools and multi-objective optimization methods are used.

1. INTRODUCTION

Piping systems play a critical role in numerous industrial infrastructures, particularly in energy, oil, and nuclear sectors. However, their structural integrity is often compromised by defects such as cracks, leading to significant failure risks, especially under complex mechanical loads like internal pressure or bending. The works of Mechab and collaborators [1–6] have demonstrated the importance of probabilistic and elasto-plastic analyses for predicting crack propagation in pipes by integrating advanced fracture mechanics models. These studies emphasize the necessity of shifting from classical deterministic methods to stochastic approaches, enabling the assessment of uncertainties related to material properties, loading conditions, and defect geometries. Concurrently, research on composite material repairs, such as the studies by Bachir Bouiadjra et al. [8,10], has shown that unilateral composite patches can significantly enhance the resistance of cracked structures, particularly for aluminum alloys used in aerospace applications. These innovative approaches, combined with precise numerical analyses [11,12], offer promising perspectives for optimizing the lifespan of structural components while reducing maintenance costs.

Simultaneously, the accumulation of plastic waste represents a major environmental challenge, with considerable ecological and economic consequences. Recent studies focus on valorizing these wastes by integrating them into novel industrial applications. For instance, research on converting plastic waste into fuels via pyrolysis [7] or into composite materials for construction [25,29] illustrates circular solutions to reduce waste while developing alternative resources. The use of high-density polyethylene (HDPE) in concrete mixtures [30] or paving blocks [29] demonstrates how recycled materials can improve mechanical and thermal properties of structures, although challenges remain regarding durability and standardization. Additionally, studies on biodegradable alternatives to conventional plastics, particularly in medical equipment [20], open pathways toward more sustainable solutions.

The convergence between these two fields—structural engineering and plastic waste management—represents an emerging research axis. For example, integrating recycled composites derived from plastic waste into pipe repair techniques could combine mechanical resilience with environmental sustainability. Studies on the mechanical properties of HDPE-based composites [25] and their behavior under load [30] suggest potential for applications in demanding environments. Furthermore, probabilistic fracture mechanics analyses [1–6] could be adapted to evaluate the long-term reliability of these innovative materials, accounting for their inherent heterogeneity.

This review highlights the interconnection between technological advancements in materials engineering and sustainability imperatives. By merging fracture analysis methodologies with strategies for plastic waste reuse, this article proposes an integrated approach to design safer and more environmentally responsible infrastructures. The contributions presented explore both theoretical models for predicting failures in cracked structures and practical applications of recycled materials, aiming to bridge the gap between technical performance and ecological responsibility.

Structural failures in piping systems, often caused by surface cracks under mechanical stress, remain a pressing issue due to their safety and economic implications. The pioneering works of Mechab et al. [1,2] detailed the mechanisms of semi-elliptical crack propagation under bending, comparing linear and non-linear analyses. These studies demonstrated that elasto-plastic models are essential for capturing the real behavior of metallic materials, particularly in critical zones near crack tips. More recently, probabilistic approaches have allowed the incorporation of variabilities in material and operational parameters, as seen in the studies of Mechab et al. [3,4], which apply these methods to longitudinal cracks subjected to internal pressure. Such research underscores the importance of quantifying failure risks to optimize inspections and maintenance strategies.

Parallel efforts to manage plastic waste have expanded, ranging from pyrolysis for fuel production [7,19] to integration into composite materials [24,25]. Studies by Petlitckaia et al. [24] on HDPE-cork composites and by V.I. et al. [29] on recycled plastic blocks illustrate how these materials can replace virgin resources while reducing waste. However, their adoption depends on meeting stringent mechanical and environmental requirements, necessitating further research to characterize their stress behavior [30].

Innovation lies in the synergistic exploitation of these two domains. For instance, composite patches for repairing cracked pipes [8,10] could be manufactured from recycled plastics, combining environmental sustainability with mechanical performance. Research on shear stresses in bonded assemblies [12] and optimization of ultrasonic testing parameters [22] provides methodological foundations to evaluate the reliability of such solutions. Additionally, predictive numerical analyses [5] could be extended to recycled composites by integrating adapted ductile damage models.

In conclusion, this article aims to explore intersections between probabilistic fracture mechanics and plastic waste utilization in engineering, proposing innovative solutions for resilient and sustainable infrastructures. The findings contribute to a holistic vision where structural safety and circular economy transitions are no longer disjointed but reinforced through interdisciplinary research.

2. Material

In this work, we used several materials commonly employed in the field of fuel transportation and the maintenance of special pipelines used for this purpose. We used materials whose characteristics are presented in the following table.

Table 1: Mechanical characteristics of the Plate.

	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	V_{12}	V_{13}	V_{23}	G_{12}(GPa)	G_{12}(GPa)	G_{12}(GPa)
Patch(carbon/	150	25	25	0.21	0.21	0.21	7.2	5.5	5.5
Adhesive(FM73)	2.55			0.32					
Pipe(SA312type304)	204			0.3					

3. Numerical simulation

ABAQUS is divided into several modules. A complete simulation in ABAQUS for a project is carried out by working successively through these modules. We will attempt to present the main modules of ABAQUS.

Let us examine the main modules of ABAQUS. Consider the repair of a pipeline using a composite patch. The external diameter of the pipeline is Do = 620 mm and the internal diameter is Di = 480 mm; the adhesive thickness is ec = 0.15 mm; the patch thickness is ep = 4 mm. The applied load and pressure are F = 50 MPa and P = 100 MPa (Fig. 1). The following table presents the properties of the parts to be modeled.

Depending on the case, an analysis may include one or more steps. The chosen mode can be static, general (for a static analysis), or dynamic explicit (for collision or impact studies).

The analysis consists of two steps in total: The first step, automatically generated by ABAQUS/CAE (Fig. 2), applies boundary conditions in terms of displacements (fixed support). The second analysis step applies a pressure of 100 MPa and a force of 50 MPa. In our case, we create a step for our part to simulate its static response under a load of 50 MPa and a pressure of 100 MPa.

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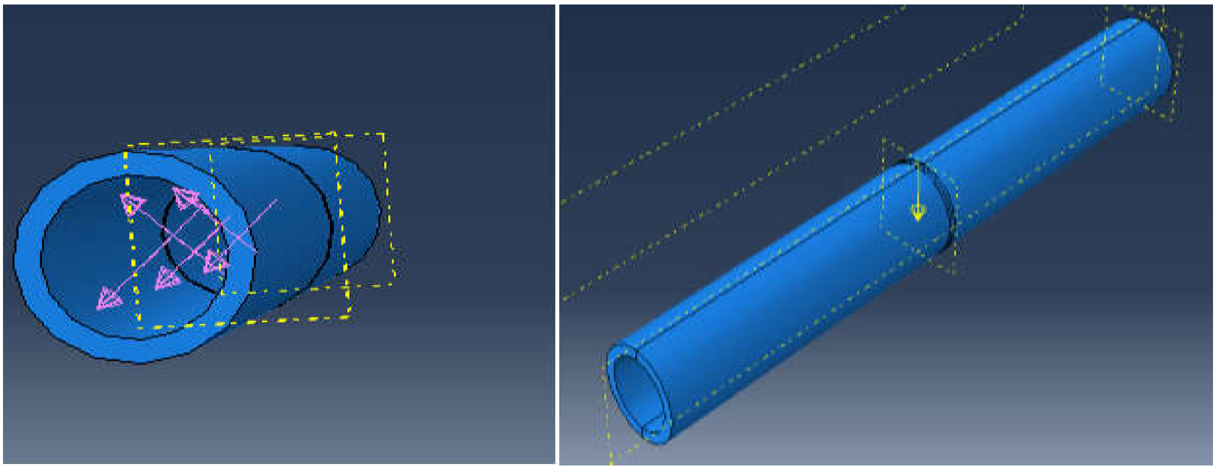

Fig. 1. applying pressure and force

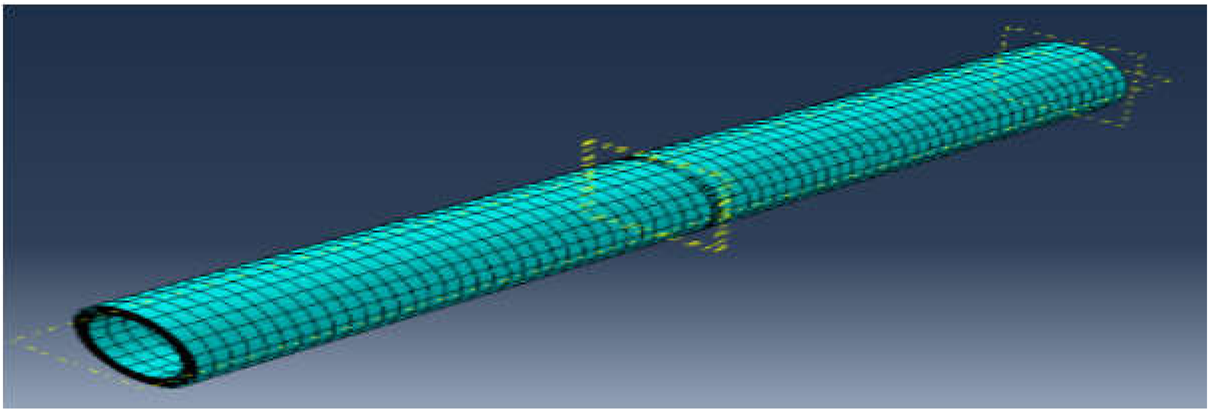

Fig. 2. Numerical modelling

4. NUMERICAL OPTIMISATION

We used numerical optimisation to predict the most important factors influencing pipeline repair thickness patch and fiber orientation we used modde5 software from the results ulistrated from ABAQUS software it is represented in the following table

Table1 Table of data

	1	2	3	4	5	6	7
	Exp No	Exp Name	Run Order	Incl/Excl	oriontation	thickness	stress intensity factor
1	1	N1	3	Incl	0	2	32
2	2	N2	11	Incl	90	2	31
3	3	N3	2	Incl	0	6	24
4	4	N4	6	Incl	90	6	23
5	5	N5	7	Incl	0	4	27
6	6	N6	8	Incl	90	4	26
7	7	N7	5	Incl	45	2	29
8	8	N8	10	Incl	45	6	19
9	9	N9	4	Incl	45	4	21
10	10	N10	1	Incl	45	4	21
11	11	N11	9	Incl	45	4	21

Table2 optimal value of the stress intensity factor in pipeline repaired

	Response	Criteria	Weight	Min	Target	Max
1	stress intensity factor	Minimize	1		18,5055	19,8736

Iteration: 5001 Iteration slider:

	1	2	3	4	5
	oriontation	thickness	stress intensity factor	iter	log(D)
1	47,3633	5,9995	19,1769	5001	-0,6104
2	47,6111	5,9996	19,1768	2138	-0,6105
3	47,1824	5,9986	19,1774	4640	-0,6098
4	47,7028	5,999	19,1771	2865	-0,6102
5	46,3555	5,9473	19,1957	1816	-0,5866
6	49,5	6	19,1842	1274	-0,6011
7	46,3555	5,9473	19,1957	1816	-0,5866
8	46,3555	5,9473	19,1957	1816	-0,5866

Table3 Coefficients list for stress intensity factor in pipeline repaired

	1	2	3	4	5
1	stress intensity factor~	Coeff. SC	Std. Err.	P	Conf. int(±)
2	Constant	4,62619	0,0512378	3,15912e-009	0,131711
3	ori	-0,0482283	0,0407762	0,290077	0,104819
4	thi	-0,426012	0,0407762	0,000138521	0,104819
5	ori*ori	0,455965	0,0627532	0,000771781	0,161313
6	thi*thi	0,180411	0,0627532	0,0347934	0,161313
7	ori*thi	-0,00351458	0,0499404	0,946623	0,128376
8					
9	N = 11	Q2 =	0,780	Cond. no. =	3,0822
10	DF = 5	R2 =	0,974	Y-miss =	0
11		R2 Adj. =	0,948	RSD =	0,0999
12				Conf. lev. =	0,95

The suggested mathematical model is :

$K=4.62619-0.0482283*ori-0.426012*thi+0.455965*ori^2+0.180411*thi^2-0.00351458*ori*thi$

Where :

K :stress intensity factor

ori :fiber orientation

thi :patch thickness

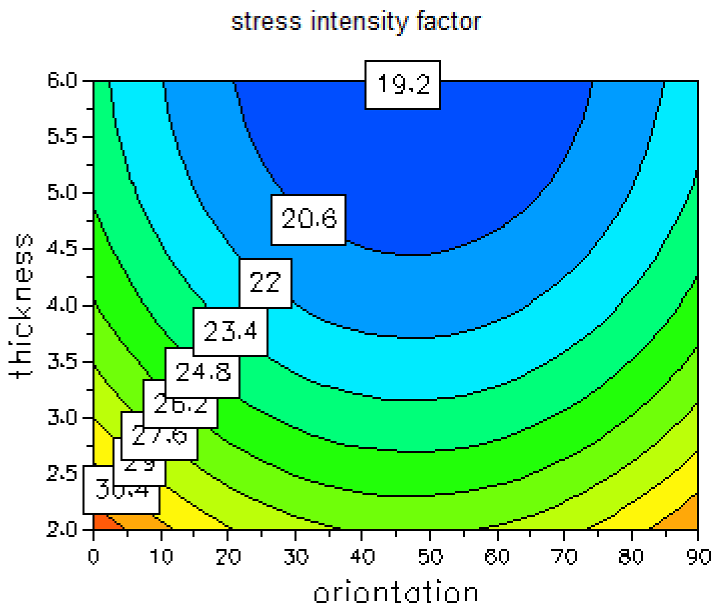

Fig3 Contour plots of the minimum stress intensity factor interaction between patch thickness and fiber orientation

Figure 3 presents a contour plot illustrating the interaction between the composite patch thickness and the fiber orientation on the minimum value of the stress intensity factor (SIF) in pipeline repair using a composite patch.
The horizontal axis corresponds to the fiber orientation (ori), while the vertical axis represents the composite patch thickness (thi).
The contour lines indicate the values of the stress intensity factor (SIF). The darker areas or lower values on the map correspond to combinations of orientation and thickness that minimize the SIF, thereby optimizing the repair.
The figure shows that the reduction of the SIF is not linear. There is a significant interaction between fiber orientation and patch thickness:
Increasing the patch thickness generally reduces the SIF, but only up to a certain point where the effect stabilizes.
The optimal fiber orientation depends on the chosen thickness: certain combinations (for example, an intermediate orientation with moderate thickness) yield the best results in terms of SIF reduction.
Mathematical model: The model ($E=4.62619-0.0482283ori-0.426012thi+0.455965ori^2+0.180411thi^2-0.00351458orithi$) reflects this complex interaction and allows the SIF to be predicted as a function of both parameters.

4. Conclusion

The study demonstrates that the repair of pipelines using composite patches is strongly influenced by the patch design parameters, particularly the thickness and fiber orientation. Numerical analysis and optimization show that:
Increasing the patch thickness allows for better absorption of stresses and reduces the stress intensity factor, but there is a threshold beyond which further improvement becomes marginal.
The fiber orientation must be carefully selected according to the thickness to achieve optimal synergy and maximize the durability of the repair.
The interaction between these two parameters is non-linear and requires a multi-objective optimization approach to identify the best combination.
Reducing the stress intensity factor with the composite patch extends the fatigue life of the repaired pipeline and improves operational safety.
In conclusion, optimizing the parameters of the composite patch (thickness and fiber orientation) is essential to ensure the mechanical efficiency and long-term reliability of pipeline repairs using composite materials. The numerical approach and the use of predictive models help guide the selection of parameters for each application case, while also paving the way for the integration of recycled materials for more sustainable and cost-effective solutions.

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