Multi-parameter analysis of cracked aluminum pipelines repaired with composite patches

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Abstract. This study presents a comprehensive numerical investigation into the reinforcement of cracked aluminum pipelines (Al 6063-T6) using bonded composite patches. A finite element model was developed in Abaqus, incorporating the mechanical behavior of aluminum and composite laminates under service-like loading conditions. The analysis first identified the dominant crack propagation mode, which was found to be mode I (opening), by evaluating stress intensity factors (K_1, K_2, K_3) for different crack orientations (0°, 45°, and 90°). Subsequent simulations focused on a comparative evaluation of three commonly used composite materials—boron, carbon, and glass—to determine the most effective in reducing the critical stress intensity factor near the crack. The influence of fiber orientation was investigated through eleven cross-ply stacking configurations ranging from 0° to 90° in 10° increments, with the 0° orientation consistently providing the most favorable results. Finally, patch geometry optimization was performed by varying the angular coverage from 45° to 360°, with the 45° configuration demonstrating the best balance between structural efficiency and material use. The findings highlight that the optimal repair configuration for aluminum pipelines is achieved with a boron patch, 0° fiber orientation, and 45° angular coverage, offering a highly effective and resource-efficient solution for structural restoration.

Keywords: Aluminum pipeline; Composite patch; Crack repair; Fiber orientation; Stress intensity factor; Finite element analysis; Optimization; Abaqus

1. Introduction

Aluminum pipelines, particularly those made of alloys such as Al 6063-T6, are increasingly used in transport and industrial networks due to their light weight, corrosion resistance, and ease of fabrication. However, under prolonged service conditions, they are not immune to structural degradation such as cracks or localized damage, which compromise both their reliability and safety. Recent works in fracture mechanics have highlighted the vulnerability of aluminum alloys under critical loading conditions, showing that crack initiation and propagation can significantly affect their performance (Moustabchir *et al*. 2018).

To mitigate such issues, bonded composite patch repair has emerged as a robust and cost-effective alternative to conventional welding or full component replacement. This approach is particularly advantageous for aluminum structures exposed to cyclic or static loads, where fatigue plays a decisive role. For instance, experimental studies have demonstrated that glass/epoxy patches can considerably extend the fatigue life of aluminum pipes (Zarrinzadeh *et al*. 2017), while shaped CFRP patches have been shown to improve fatigue resistance and stiffness recovery (Liu *et al*. 2017).

The efficiency of composite patch repair is strongly influenced by multiple parameters, including patch material, fiber orientation, and geometric configuration. Investigations on GFRP-repaired pipelines revealed that fiber alignment in the [0°] direction offers superior resistance to crack growth under internal pressure (Abd-Elhady *et al*. 2020). Similarly, numerical studies emphasized the role of patch dimensions and thickness in reducing stress concentrations and enhancing pressure-bearing capacity (Saffar *et al*. 2019, Chen *et al*. 2021).

Another important aspect concerns the predictive tools used to evaluate crack growth and burst pressure in defective pipelines. Extended finite element methods (XFEM) have shown high reliability in modeling crack propagation trajectories and estimating critical pressures (Okodi *et al*. 2020, Valadi *et al*. 2018). More recent advances even integrate acoustic emission monitoring to predict fatigue crack propagation in real time, providing valuable insights for structural health monitoring (Yan *et al*. 2024).

The optimization of composite repair further extends to the choice of fiber architecture. Research has demonstrated that bidirectional or hybrid stacking sequences offer better stress redistribution compared to unidirectional configurations, thereby improving burst pressure and delaying crack instability (Shahid *et al*. 2025, Kaci *et al*. 2017). Other works highlighted that multi-parameter optimization—considering patch width, thickness, and stiffness ratio—leads to significant improvements in crack stability while minimizing the additional structural weight (Talebi and Abedian. 2017).

Experimental validations continue to confirm the reliability of composite reinforcement. For example, burst tests and numerical simulations consistently report increases in pressure resistance of up to 20–30% when optimized fiber orientations and patch geometries are applied (Lim *et al*. 2019, Shafaee Fallah *et al*. 2023). Furthermore, composite patches have proven effective across a wide range of defect types and service conditions, with their performance highly dependent on adhesion quality and curing processes (El-Sagheer *et al*. 2020, Shabibi *et al*. 2024).

Taken together, these contributions demonstrate that the repair of aluminum pipelines through composite patches is a promising solution that requires a careful balance of material selection, fiber orientation, adhesive performance, and patch geometry. The present study builds on this foundation by performing a detailed finite element analysis of cracked Al 6063-T6 pipelines repaired with boron, carbon, and glass fiber composites. Special emphasis is placed on evaluating fiber orientations, identifying the dominant crack mode, and optimizing the angular coverage of the patch in order to achieve an effective and economical repair strategy.

2. Problem statement and objectives

Despite numerous advances reported in the literature, most existing works focus on the isolated study of specific parameters such as the patch material, fiber orientation, or repair geometry. This fragmented approach does not capture the complex interactions between these variables, which in reality govern the overall effectiveness of the reinforcement. In particular, for pipelines made of aluminum alloys, whose mechanical behavior differs significantly from that of traditional steels, this lack of an integrated perspective represents a major limitation for the development of reliable and optimized repair strategies.

To address this gap, the present work proposes a comprehensive numerical analysis of the repair of cracked pipelines made of aluminum alloy 6063-T6 using composite patches. The study aims to quantify the combined effect of several critical parameters on the reduction of the stress intensity factor, which is the key parameter controlling crack propagation.

In this context, the finite element model developed in Abaqus first investigates the dominant crack propagation mode through the evaluation of the components K1, K2, and K3 for different crack orientations. It then compares the mechanical performance of three patch materials, namely glass, carbon, and boron. The study further explores the effect of fiber orientation through a systematic analysis of eleven cross-ply stacking sequences, ranging from 0° to 90° in increments of 10°. Finally, a geometric optimization is performed by varying the angular coverage of the patch in order to determine the most efficient configuration that ensures effective reinforcement while minimizing composite material usage.

The objective of this multiparametric approach is to establish a robust and generalized methodology capable of guiding the selection of the patch material, fiber architecture, and geometric configuration. The ultimate goal is to achieve composite repairs that are not only mechanically efficient but also durable and specifically adapted to the operational constraints of aluminum pipelines.

3. Materials and models

3.1. Definition of the Pipeline Model

3.1.1. Mechanical Properties of the Base Alloy

At the outset of this investigation, it is necessary to establish the mechanical characteristics of the aluminum pipeline under consideration. The structure is idealized as a hollow cylindrical tube with an outer diameter of 50 mm, an inner diameter of 49 mm, and a total length of 200 mm, representing a typical pressurized conduit encountered in engineering applications. The aluminum alloy Al 6063-T6, selected as the base material, is assumed to behave as an isotropic and linearly elastic medium. The adopted mechanical properties for this alloy are reported in Table 1 (Singh *et al*. 2015).

Table 1 Mechanical properties of the aluminum pipeline material

Young's Modulus (MPa)	Poisson's Ratio
70000	0.3

These parameters form the fundamental basis for all subsequent simulations and allow accurate assessment of the stress intensity and crack propagation behavior of the repaired and unrepaired pipeline.

3.1.2. Geometrical Representation of the Structure

The cracked pipeline was modeled using Abaqus to create a precise three-dimensional representation of the structure. The pipeline is idealized as a hollow cylindrical body with a total length of 200 mm, an outer diameter of 50 mm, and an inner diameter of 49 mm, consistent with the predefined specifications. The geometric configuration of the aluminum pipeline is displayed in Figure 1.

The crack was carefully incorporated into the external surface of the model in a parametric manner, which makes it possible to evaluate its mechanical response under various orientations. Three angular positions of the crack were examined, namely 0°, 45°, and 90° with respect to the longitudinal axis of the pipe. This strategy provides a systematic way to determine the most critical crack orientation before introducing the composite repair patches.

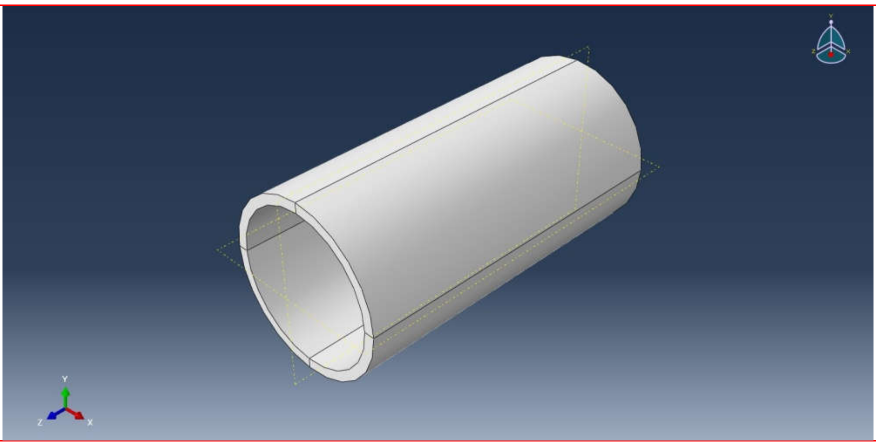


Fig. 1 Geometric model of the cracked aluminum pipeline

3.1.3. Applied Loads and Boundary Constraints

In this numerical study, the loading and boundary conditions were carefully designed to replicate the service environment of an aluminum pipeline subjected to internal pressure. The two ends of the pipeline are completely constrained, preventing both translational and rotational movement. This configuration ensures global stability of the model while focusing the analysis on the cracked region where stress redistribution occurs.

The internal pressure is introduced as a uniformly distributed load applied over the entire inner cylindrical surface of the pipeline. Within the Abaqus environment, this load is defined as a *Pressure* type with a constant magnitude of 10 MPa. To mimic realistic pressurization during pipeline operation, a “Ramp” amplitude function is assigned, allowing the pressure to increase progressively rather than instantaneously.

Together, the applied pressure and the fixed-end conditions recreate a realistic stress field representative of in-service pipelines. Figure 2 provides a schematic illustration of the boundary constraints and loading conditions implemented in this finite element model.

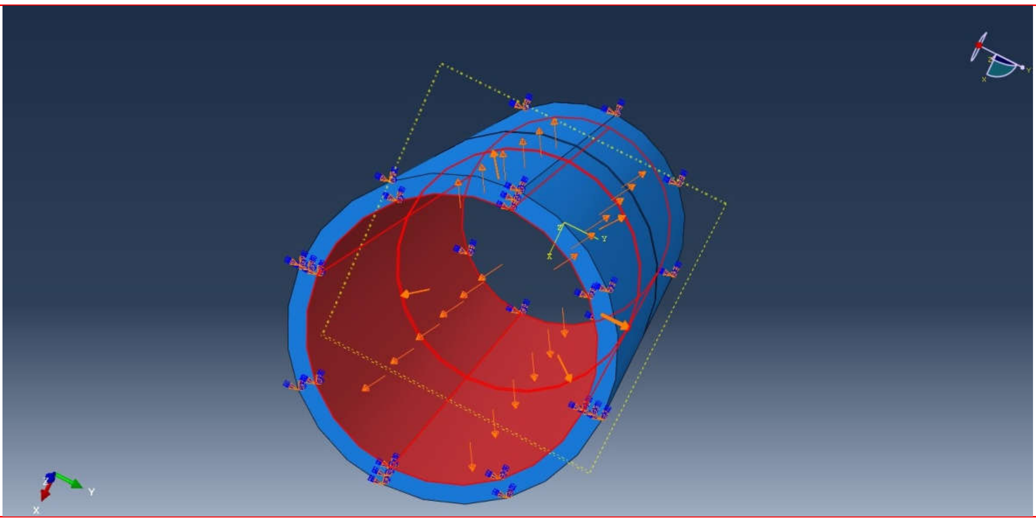


Fig. 2 Schematic representation of the applied internal pressure and boundary constraints on the pipeline

3.2 Preliminary Analysis of the Unrepaired Pipeline

3.2.1. Evaluation of Stress Intensity Factors

To better characterize the mechanical behavior of the cracked pipeline in its unrepaired state, numerical simulations were performed in Abaqus in order to evaluate the stress intensity factors. This analysis allows determining the predominant fracture mode by examining the intensity components at the crack front, distinguishing between mode I (opening), mode II (in-plane shear), and mode III (out-of-plane shear).

For this purpose, three configurations of the pipeline were modeled, each corresponding to a different crack orientation on the external surface of the tube. The orientations considered were 0°, 45°, and 90°, defined with respect to the longitudinal axis of the pipeline. The corresponding results provided the values of the stress intensity factors associated with each case, making it possible to identify the most critical cracking mode.

Figs. 3(a)–(b)–(c) present the three angular orientations of the crack on the outer surface of the pipeline, namely 0°, 45°, and 90°. These configurations are essential references for interpreting the numerical results and will serve as the foundation for the subsequent repair strategy using composite patches.

(a) Crack orientation of 0° (b) Crack orientation of 45° (c) Crack orientation of 90°

Fig. 3 Schematic representation of the crack orientations on the outer surface of the pipeline

3.2.2. Determination of the Most Critical Crack Orientation

The purpose of this stage is to determine which of the predefined crack orientations represents the most severe case for the pipeline subjected to internal pressurization. No additional simulations are required at this point since the three configurations (0°, 45°, and 90°) were already analyzed in the previous subsection dedicated to stress intensity factor evaluation.

The comparative assessment is carried out using the results obtained earlier, while considering the dominant fracture mode identified in Section 3.2.1. For each crack orientation, the corresponding stress intensity factor values at the crack front are examined and compared. The orientation producing the highest stress level, consistent with the prevailing fracture mode, is considered the most critical. This orientation is therefore retained as the reference case for the continuation of the work, especially in the subsequent reinforcement and optimization analyses using composite patches.

3.3. Implementation of the Composite Repair System

3.3.1. Choice of Patch Materials for Repair

In the context of this study, three types of composite materials are investigated for use in the repair patches: boron fiber composite, carbon fiber composite, and glass fiber composite. These materials were chosen because of their widespread application in structural reinforcement as well as their well-documented mechanical properties. The detailed characteristics of each material are provided in Table 2 (Sadek *et al*. 2018, Yousefi *et al*. 2021, Hu *et al*. 2021). These properties establish the foundation for the comparative analysis conducted in this work, with the ultimate objective of identifying the composite material that delivers the most effective stress mitigation when applied to the repair of cracked aluminum pipelines.

Table 2 Comparative mechanical properties of boron, carbon, and glass fiber composite patches

	E1(MPa)	E2(MPa)	v12	G12(MPa)	G13(MPa)	G23(MPa)
Boron	200000	19600	0.3	7200	5500	5500
Glass	45000	12000	0.28	5000	5000	5600
Carbon	125000	11300	0.3	5430	5430	3980

3.3.2. Patch Geometry Definition and Modeling

The composite patch was represented in Abaqus by adapting its geometry to the cylindrical configuration of the aluminum pipeline. Positioned directly over the cracked region, the patch adheres to the external wall of the tube and matches its curvature, thereby ensuring mechanical compatibility between the base structure and the reinforcement. While the pipeline is a full cylinder of 360°, the repair patch was designed to cover a circumferential sector of 90°, corresponding to one-quarter of the pipe's perimeter. This choice balances effective crack coverage with material efficiency.

The patch itself was modeled as a partial ring with a constant thickness of 1.5 mm, constructed from eight laminated plies. All plies were initially aligned at 0°, i.e., parallel to the longitudinal axis of the pipeline, to provide maximum reinforcement in the principal loading direction. This baseline configuration is used as the reference for further studies involving alternative fiber orientations and variations in angular coverage.

The geometric arrangement of the patch bonded to the pipeline is shown in Fig. 4, which illustrates its placement and extension over the cracked surface in the finite element model.

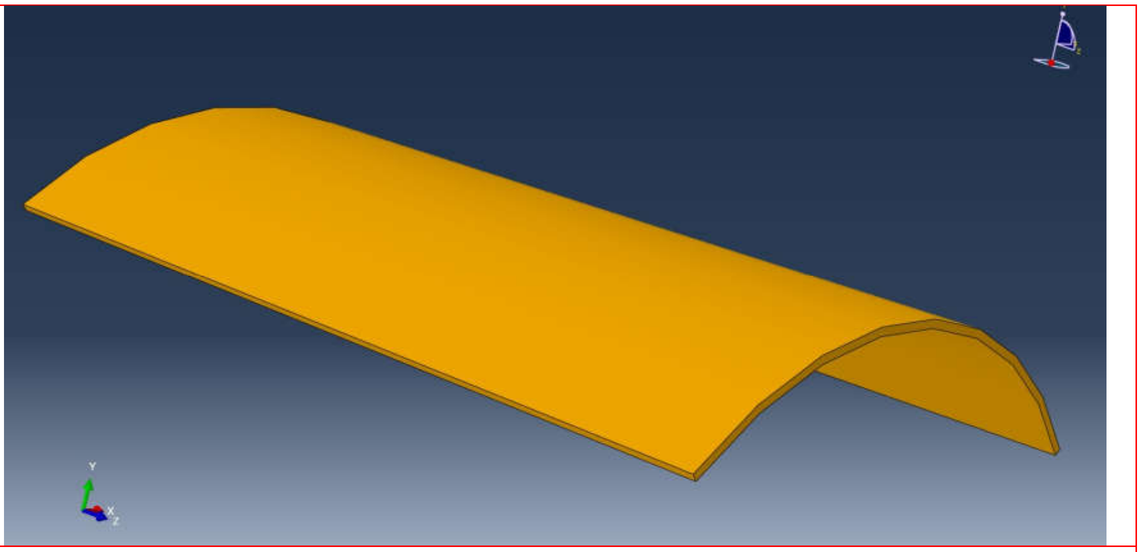


Fig. 4 Geometric representation of the composite patch

3.3.3. Bonding of the Composite Patch to the Pipeline Surface

In this study, the integration of the composite patch with the aluminum pipeline is achieved by adhesively bonding it directly to the outer wall, precisely aligned with the crack region. The connection is ensured using the FM300 structural adhesive, which is a thermosetting epoxy film widely adopted in aerospace and civil engineering applications due to its superior mechanical resistance and long-term durability under severe service conditions. Employing this adhesive guarantees efficient load transfer between the metallic substrate and the composite reinforcement, while maintaining stability when the pipeline is subjected to internal pressurization.

The mechanical characteristics of the adhesive implemented in this model are summarized in Table 3 (Hoang *et al*. 2023). A schematic representation of the bonded configuration between the patch and the damaged pipe is provided in Fig. 5, showing how the repair system is incorporated into the finite element model.

Table 3 Mechanical properties of the adhesive

Young's Modulus (MPa)	Poisson's Ratio
3500	0.38

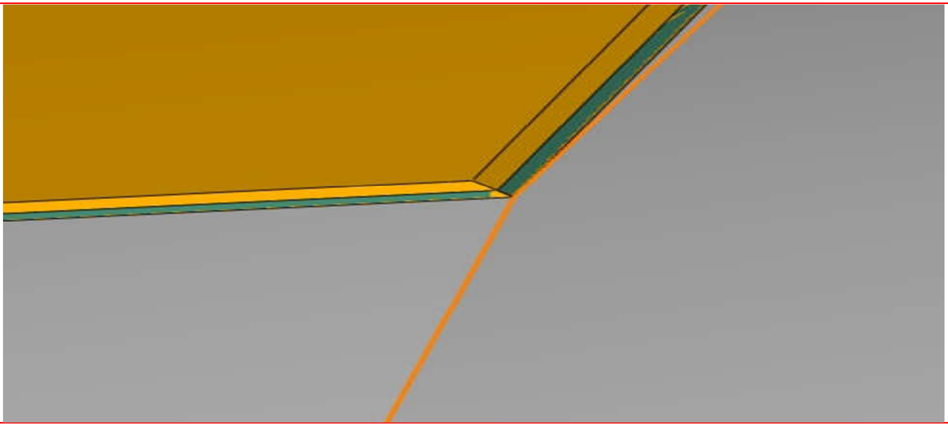


Fig. 5 Geometric assembly of the pipeline and the composite patch

3.3.4. Finite element discretization of the pipeline–patch system

In the finite element modeling stage, particular emphasis was placed on the meshing strategy to guarantee reliable and accurate numerical predictions. The complete system—comprising the aluminum pipeline, the composite reinforcement patch, and the adhesive film—was discretized using three-dimensional solid elements. To properly capture stress gradients and potential singularities, a denser mesh was applied in the vicinity of the crack front and along the patch–pipeline adhesive interface, while a coarser distribution was maintained in less critical areas.

A convergence analysis was conducted to establish an appropriate element size, ensuring a compromise between computational efficiency and the accuracy of the calculated stress intensity factors. Refinement was carried out progressively until the difference in the obtained values of K1 between two consecutive refinements was within 2%. The final mesh configuration combined structured hexahedral elements in the regular zones with unstructured tetrahedral elements in regions of high geometric complexity, notably around the crack tip and patch borders.

The final meshed model of the repaired pipeline, highlighting the refinement in critical zones, is illustrated in Fig. 6.

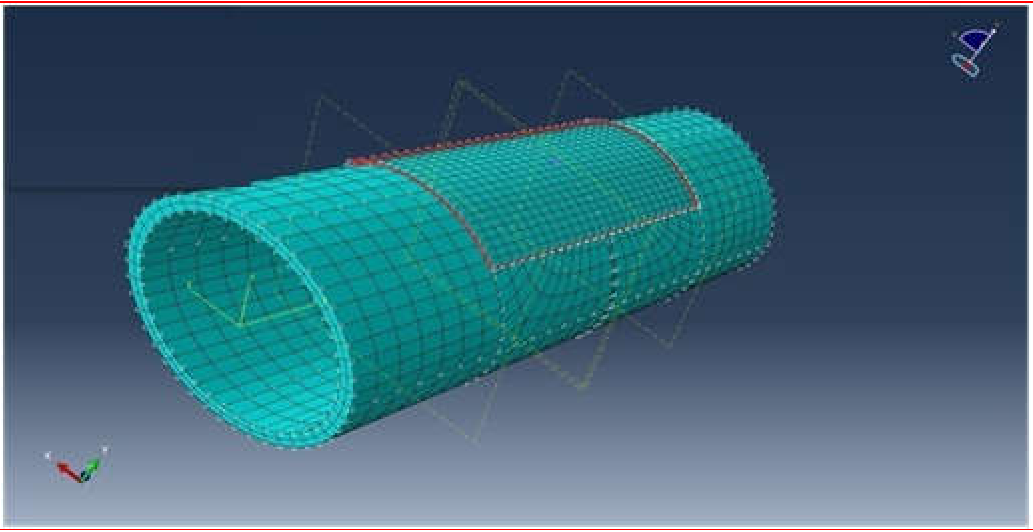


Fig. 6 Meshed model of the pipeline–patch assembly

3.4. Multi-Parameter Optimization of the Repair Strategy

The last stage of the methodology focuses on enhancing the global efficiency of the composite patch used to repair the cracked pipeline. The optimization procedure is conducted in successive steps to ensure a structured and progressive improvement in mechanical response.

The first step consists of a parametric investigation of fiber orientation within the laminate plies. Several angular arrangements are tested to identify the most effective configuration for reducing stress intensity. This analysis is systematically performed for each of the three candidate patch materials: boron, carbon, and glass.

After establishing the optimal fiber orientation, the next stage involves a comparative evaluation of the patch materials. The goal is to select the material that delivers the greatest reduction in local stresses surrounding the crack zone.

Finally, with the material and fiber orientation determined, the optimization process turns to the patch geometry. More specifically, the angular coverage of the patch on the pipe's surface is adjusted to balance two objectives: maximizing reinforcement efficiency and minimizing composite consumption.

3.4.1. Influence of Fiber Orientation through Cross-Ply Stacking

The first stage of the optimization procedure investigates how fiber orientation affects the performance of the composite patch. The main goal is to determine the angular configuration that most effectively enhances the structural resistance of the cracked pipeline.

To this end, a set of parametric simulations is performed using a symmetric cross-ply stacking sequence of the form $[+\theta/-\theta]$ applied to eight plies. Eleven orientations are tested, covering angles from 0° to 90° in increments of 10°, with the inclusion of the intermediate case at 45°.

This analysis is carried out independently for the three selected composite materials: boron, carbon, and glass. For each material, the influence of fiber orientation on the reduction of stress intensity factors near the crack tip is assessed under identical conditions of boundary constraints, patch geometry, and modeling approach.

The outcomes of this step allow the identification of the most suitable fiber orientation for each material, providing a clear understanding of how angular stacking affects the ability of the patch to redistribute stresses and mitigate crack propagation.

3.4.2. Comparative Assessment of Patch Materials

Once the most effective fiber orientation has been established for each case, the optimization process proceeds with the selection of the most suitable composite material. The material choice plays a decisive role, as it governs the stiffness of the repair system, its resistance to delamination, and its overall structural performance.

In this investigation, three fiber-reinforced composites are analyzed: boron, carbon, and glass. To guarantee fairness in the evaluation, the simulations for all three materials are performed using their respective optimal fiber orientations identified in the previous stage. The boundary conditions, patch geometry, and bonding configuration remain identical across all cases, ensuring that the only variable under study is the material itself.

The numerical results are examined in terms of stress reduction near the crack tip, with particular emphasis on the opening-mode component of the stress intensity factor. Beyond simply quantifying the reduction of critical stresses, the analysis also considers the capacity of each material to redistribute loads uniformly around the damaged zone, thereby mitigating stress concentration.

At the conclusion of this comparative phase, the material that demonstrates the highest mechanical efficiency and compatibility with the cracked aluminum pipeline will be selected. This optimal choice will serve as the foundation for the final stage of optimization, dedicated to defining the most effective angular coverage of the patch.

3.4.3. Optimization of the Patch Angular Coverage

Once the optimal patch material and fiber orientation have been determined, the final step of the optimization process focuses on defining the angular extent of the composite reinforcement on the pipeline surface.

The purpose of this phase is to identify the most efficient balance between mechanical reinforcement and the economical use of composite material. To this end, a parametric investigation is conducted by varying the circumferential coverage angle of the patch around the pipe.

Eight configurations are considered, with angular coverages of 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°. Each configuration modifies the proportion of the pipe circumference covered, thereby enabling a detailed evaluation of its effect on stress redistribution in the cracked zone.

All cases are simulated under identical conditions, with the same optimized material and fiber orientation as determined in the earlier steps. This ensures that the only parameter under examination is the angular extent of the patch.

Fig. 7 illustrates the eight different reinforcement configurations, highlighting the gradual increase in angular coverage applied to the pipeline surface.

Through this analysis, it becomes possible to determine the minimum angular coverage that ensures a substantial reduction of critical stresses, while avoiding unnecessary use of composite material and thus optimizing both performance and cost-efficiency.

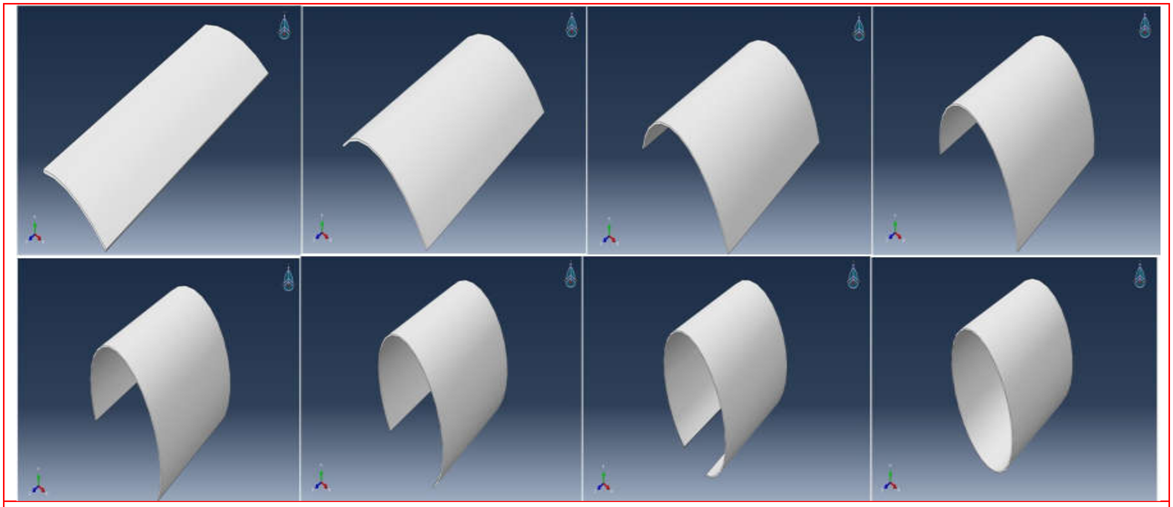


Fig. 7 Schematic representation of the composite patch with eight angular coverages ranging from 45° to 360°.

4. Results and Discussions

4.1. Preliminary Evaluation of the Damaged Pipeline

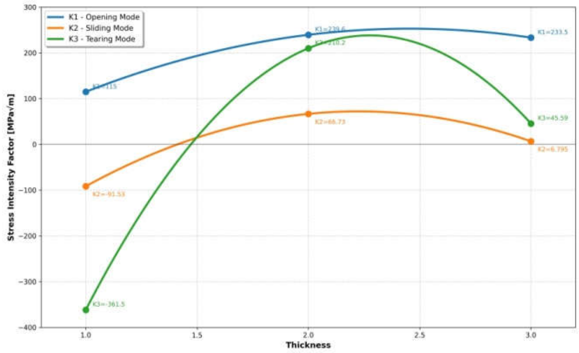
4.1.1. Determination of the Dominant Fracture Mode in the Unreinforced Pipeline

The first stage of the investigation focuses on evaluating the fracture behavior of the aluminum pipeline prior to any reinforcement. The objective of this step is to determine which fracture mode governs crack propagation by analyzing the stress intensity factors (SIFs). Three angular orientations of the surface crack were considered relative to the longitudinal axis of the tube: 0°, 45°, and 90°.

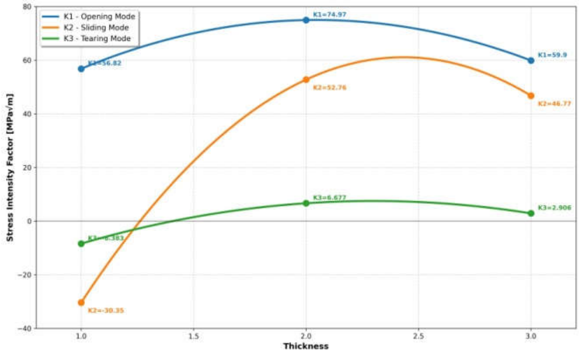
For each orientation, the SIF components—K_1 (mode I, opening), K_2 (mode II, in-plane shear), and K_3 (mode III, out-of-plane shear)—were extracted along the crack front. A comparative examination of these values highlights that the opening mode (K_1) is systematically higher than K_2 and K_3 across all configurations. This trend indicates that the pipeline's failure mechanism is mainly governed by mode I fracture.

Quantitatively, the 0° orientation recorded the highest K_1 value (115), which is almost double that at 45° (56.8, +102%) and over three times that at 90° (37.3, +208%). Such a disparity confirms that the longitudinal crack orientation is the most critical case to be considered in subsequent reinforcement analyses.

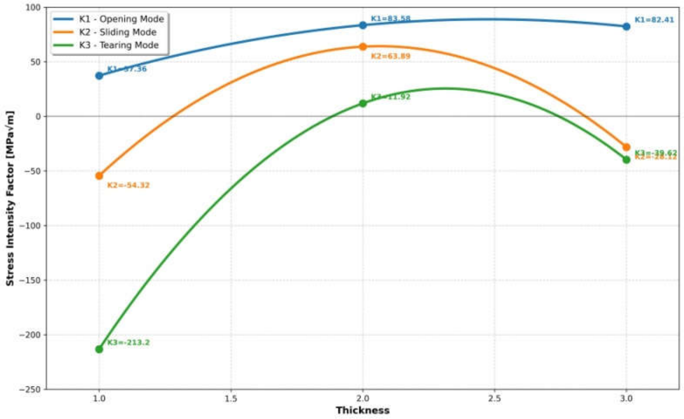
Figs. 8(a)-(b)-(c) display the comparative plots of SIFs for the three orientations. These figures clearly illustrate the predominance of K_1 over K_2 and K_3, thereby validating that mode I (opening) governs the crack propagation mechanism in the unrepaired pipeline.



(a) Crack orientation of 0°



(b) Crack orientation of 45°



(c) Crack orientation of 90°

Fig. 8 Stress intensity factor distribution across different crack orientations

4.1.2. Selection of the Most Severe Crack Orientation

Building upon the fracture mode analysis, a comparative evaluation was carried out for the three crack orientations studied, namely 0°, 45°, and 90°, in order to determine which configuration represents the most critical mechanical condition for the pipeline under internal pressure. The assessment specifically focuses on the mode I stress intensity factor (K_1), previously identified as the dominant fracture component.

The K_1 values obtained for each orientation were extracted from the numerical simulations and plotted for direct comparison. This analysis reveals a clear trend: the crack aligned at 0° relative to the longitudinal axis of the pipeline consistently generates the highest opening stresses. In contrast, the 45° and 90° orientations exhibit noticeably lower values of K_1, indicating less severe conditions for crack propagation.

The graphical synthesis presented in Fig. 9 highlights this distinction, showing the sharp predominance of the 0° orientation in terms of stress intensity. Based on these results, the 0° crack orientation is identified as the most severe case, and is therefore adopted as the reference configuration for all subsequent repair and optimization stages in this study.

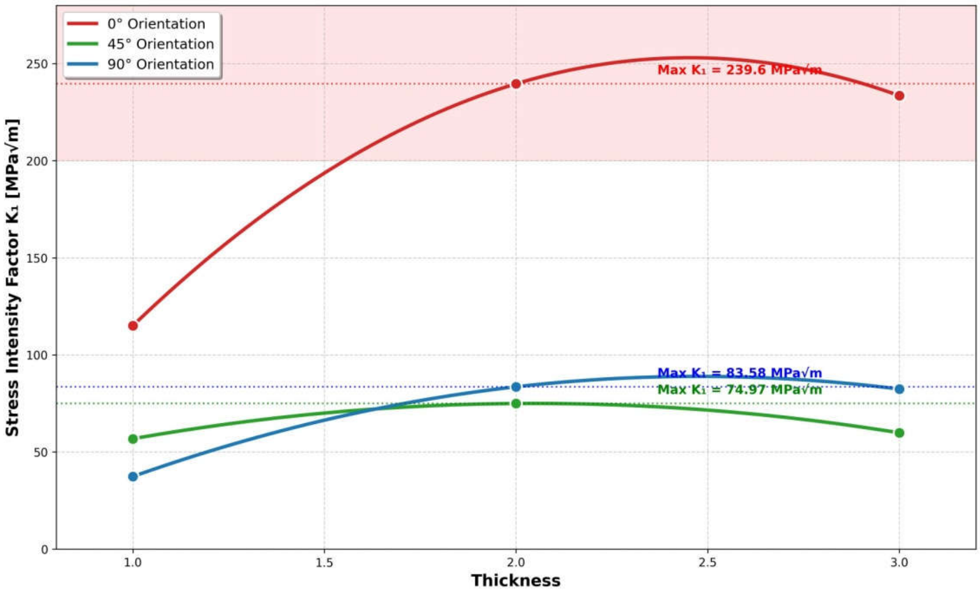


Fig. 9 Comparative analysis of stress intensity factor K_I for the three crack orientations (0°, 45°, 90°).

4.1.3. Graphical Representation of the Crack State

To complement the numerical analyses, a graphical depiction of the pipeline crack is presented in order to clearly illustrate its geometrical configuration within the model. The defect was parametrically introduced on the outer surface of the tube, ensuring consistency with the most critical orientation identified in the previous section.

Fig. 10 shows the spatial representation of the crack integrated into the Abaqus model. This visualization highlights the precise location of the crack along the pipeline wall, as well as its orientation relative to the longitudinal axis. Such representation provides a clear understanding of the defect geometry and its role in the stress distribution within the structure.

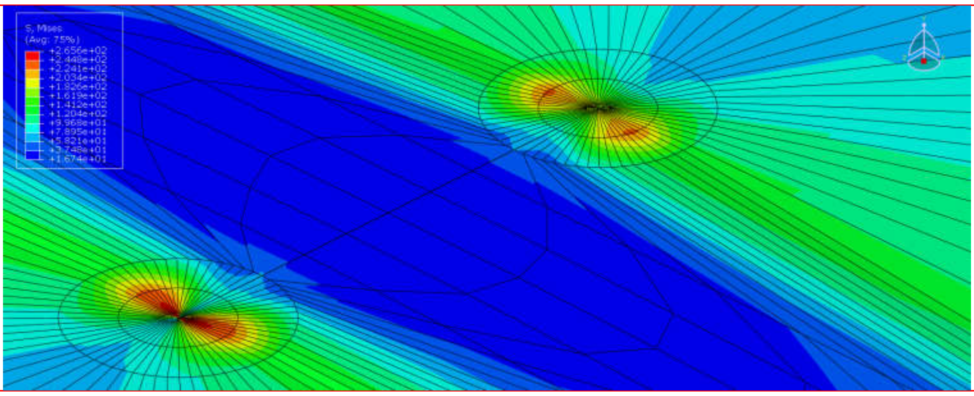


Fig. 10 Graphical representation of the crack on the pipeline surface

4.2. Patch Parametric Optimization of the Composite Reinforcement

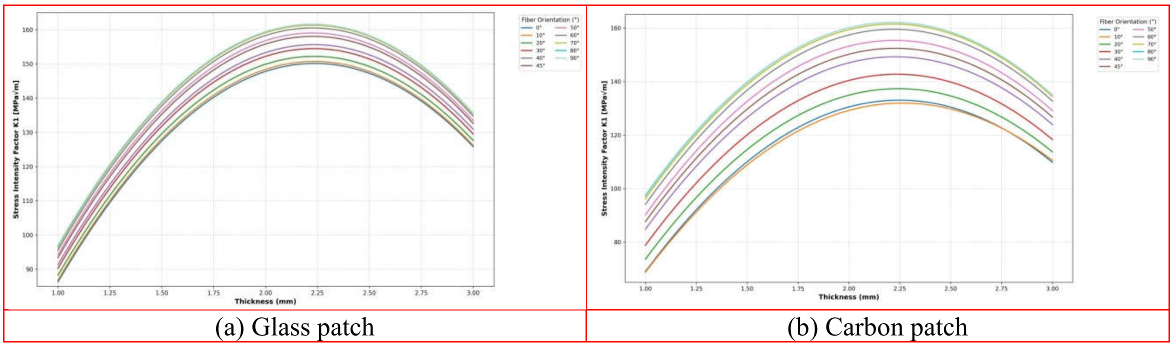
4.2.1. Effect of Fiber Orientation on the Repair Efficiency

The first stage of the optimization process focused on analyzing the influence of fiber orientation within the composite patch on the mechanical behavior of the repaired aluminum pipeline. Three types of composites were considered glass, carbon, and boron and for each material, eleven different fiber orientations were investigated. These orientations were defined through symmetric cross-ply stacking sequences varying from 0° to 90° in increments of 10°. The simulations were performed under identical boundary conditions, using the same patch geometry and the same crack orientation previously identified as critical.

The obtained results are synthesized in Figs. 11(a)-(b)-(c), which illustrate the variation of the stress intensity factor K_1 with fiber orientation for each material. Each curve shows that K_1 decreases significantly when the fibers are aligned at 0° with the longitudinal axis of the pipeline, whereas higher angles systematically lead to larger K_1 values. This trend indicates that the effectiveness of the patch diminishes as the fibers deviate from the primary loading direction.

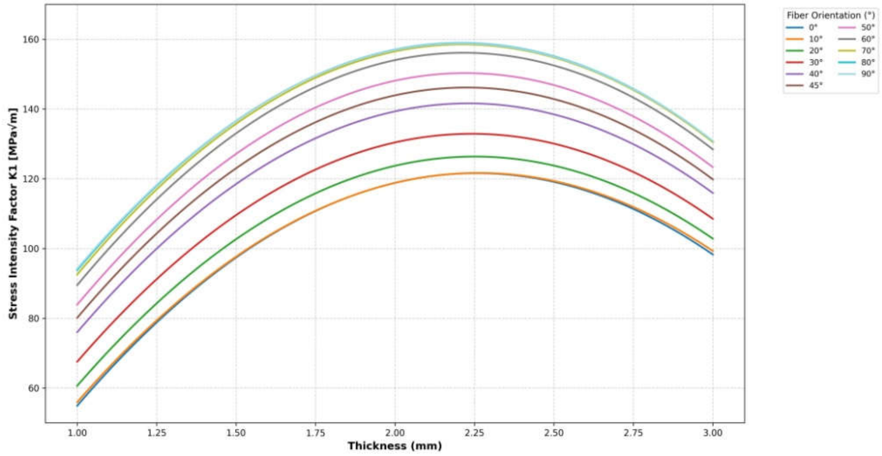
Quantitatively, the reduction of K_1 at 0° is the most pronounced across all three materials, confirming that this configuration provides the greatest resistance against crack opening. In contrast, orientations close to 90° exhibit up to 40–50% higher K_1 values compared to the 0° case, highlighting the loss of reinforcement efficiency.

These findings clearly demonstrate that fiber alignment with the principal stress direction is a key factor for maximizing repair performance. Consequently, the 0° orientation is retained for all subsequent simulations, serving as the baseline configuration for both material selection and patch geometry optimization.



(a) Glass patch

(b) Carbon patch



(c) Boron patch

Fig. 11 Variation of stress intensity factor K_1 for glass, carbon, and boron composite patches with different fiber orientations.

4.2.2. Comparative Assessment of Candidate Composite Materials

Following the identification of 0° as the optimal fiber orientation, a comparative evaluation was performed to determine the most effective composite material for repairing the cracked aluminum pipeline. The three materials retained for this assessment were boron, carbon, and glass fiber composites.

In this stage, all simulations were conducted with the fibers aligned at 0°, under identical loading and boundary conditions, to ensure an objective comparison. The results highlighted noticeable differences in the ability of each material to reduce the stress intensity factor K1 at the crack front.

Among the three candidates, the boron-based patch demonstrated the most pronounced efficiency, achieving a significantly greater reduction of K1 compared to its carbon and glass counterparts. This performance is primarily attributed to the superior stiffness and higher elastic modulus of boron, which enhances its ability to withstand crack opening stresses and redistribute loads around the defect.

The comparative results are illustrated in Fig. 12, which clearly confirms the dominance of the boron patch in minimizing crack propagation tendencies. Based on these findings, boron is retained as the reference material for the subsequent optimization of the patch’s angular dimension.

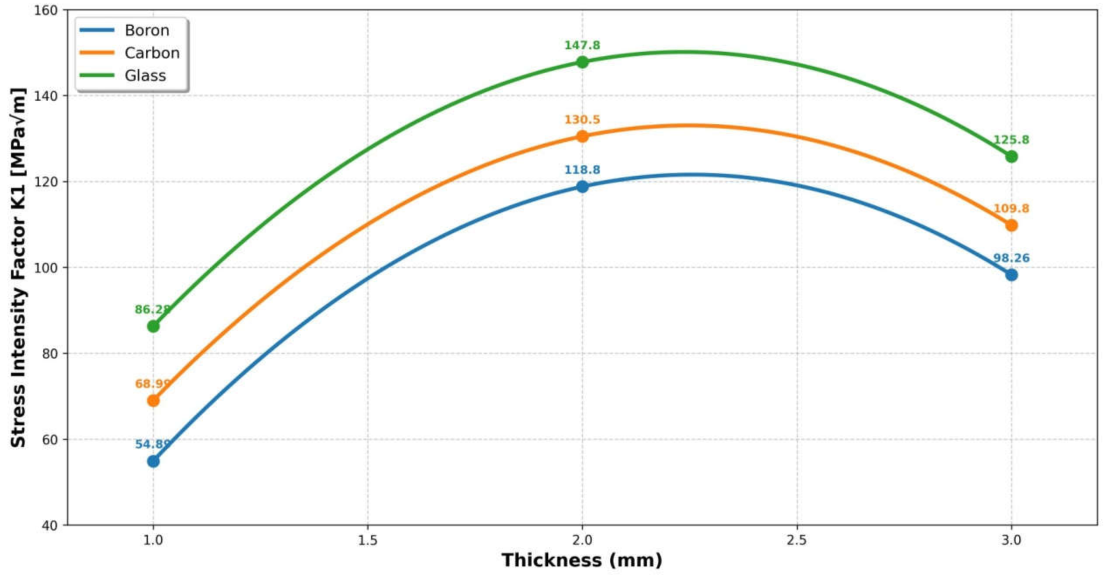


Fig. 12 Comparative evaluation of stress intensity factor K1 for boron, carbon, and glass patches under the optimal fiber orientation (0°).

4.2.3. Determination of the Optimal Angular Extension of the Patch

With the optimal material (boron) and fiber orientation (0°) established, the focus shifts to refining the angular extension of the composite patch applied on the pipeline's external wall. This step is crucial for achieving the best compromise between repair performance and material efficiency.

Eight patch configurations were evaluated, corresponding to angular coverages of 45°, 90°, 135°, 180°, 225°, 270°, 315°, and 360°. Each simulation was conducted under identical boundary conditions and using the same modeling assumptions as in the previous optimization phases.

The results reveal a clear trend: as the angular coverage of the patch increases, the stress intensity factor K1 decreases, reflecting improved reinforcement efficiency. Nevertheless, the gain in performance is not linear. Beyond 45°, additional coverage leads only to marginal improvements, with reductions of less than 5% when increasing from 90° up to 360°.

This observation highlights that a 45° patch already achieves nearly the same effectiveness as full circumferential coverage, reducing K1 to values very close to those obtained with the 360° configuration. In practical terms, this means the repair can be optimized without excessive use of composite material, ensuring both efficiency and economic viability.

Fig. 13 presents the variation of the stress intensity factor K1 with respect to the angular extension of the patch, confirming that the 45° configuration provides the most efficient balance between reinforcement capacity and material consumption.

In summary, the optimal repair strategy is achieved with a boron patch oriented at 0° fibers and covering 45° of the pipeline circumference, offering maximum reinforcement efficiency with minimum material usage.

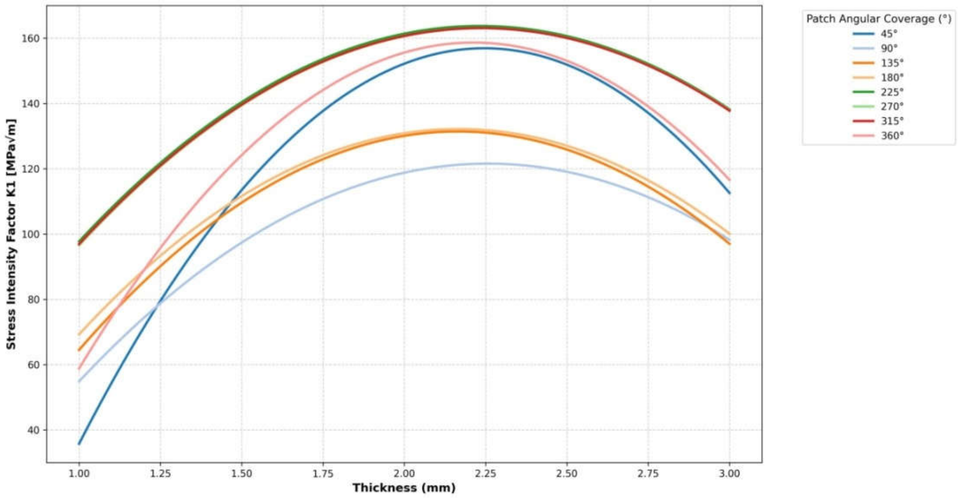


Fig. 13 Variation of the stress intensity factor K_I with respect to the angular coverage of the composite patch.

4.3. Consolidated Optimal Repair Strategy

4.3.1. Summary of the Optimized Repair Configuration

The successive optimization steps carried out in this work made it possible to define the most efficient repair strategy for the cracked aluminum pipeline. The results clearly highlight boron composite as the best performing material, owing to its high stiffness and superior capability to suppress the stress intensity factor in the vicinity of the defect.

Regarding the fiber arrangement, the orientation at 0° relative to the pipeline axis proved consistently to provide the greatest decrease in opening stresses (mode I) across all tested materials, confirming the importance of aligning fibers with the principal loading direction.

Finally, the study of patch angular coverage demonstrated that extending the reinforcement over 45° of the pipe circumference is sufficient to achieve nearly the same efficiency as larger coverages, while drastically reducing the amount of composite material required.

In conclusion, the optimal repair configuration consists of a boron composite patch, designed with fibers oriented at 0°, and covering an angular span of 45° on the external surface of the pipeline. This combination offers the best compromise between structural efficiency and material economy.

4.3.2. Numerical Illustration of the Optimized Repair Applied to the Pipeline

Following the previous visualization of the crack in its unreinforced state, this section presents the numerical depiction of the final repair configuration using the optimized composite patch. Fig. 14 illustrates the application of a boron patch, with fibers aligned at 0° relative to the pipeline axis, covering an angular sector of 45° along the circumference.

The figure clearly demonstrates the improvement achieved after reinforcement, showing a substantial decrease in crack opening and a marked reduction in stress concentration at the defect location. When compared with the initial unrepaired configuration, the model highlights the capacity of the patch to effectively redistribute stresses, thereby limiting the risk of further crack growth.

This numerical visualization provides a qualitative validation of the optimized repair solution. It confirms that the selected configuration boron composite, 0° fiber orientation, and 45° coverage offers a well-balanced combination of mechanical efficiency and material optimization, ensuring effective reinforcement of the pipeline structure.

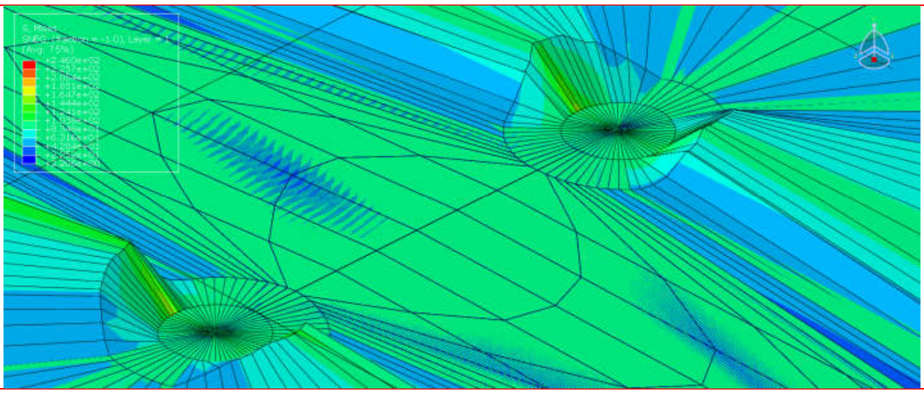


Fig. 14 Numerical illustration of the repaired pipeline using the optimal composite patch configuration

5. Conclusion

The structural rehabilitation of cracked aluminum pipelines represents a significant engineering challenge, especially in industries where safety and reliability are paramount. This work proposed a detailed numerical framework to design and optimize composite patch repairs for Al 6063-T6 pipelines subjected to internal pressure. The methodology integrated the effects of crack orientation, fiber architecture, patch material, and geometric coverage in order to identify the most effective repair configuration.

The preliminary analysis of the unreinforced pipeline established that the dominant fracture mechanism corresponds to mode I (opening), with the 0° crack orientation identified as the most critical configuration. Based on this reference case, a series of simulations explored the role of fiber orientation, showing that alignment at 0° consistently minimized the stress intensity factor K_I, regardless of whether boron, carbon, or glass composites were employed.

When comparing patch materials, boron composites demonstrated superior efficiency in attenuating critical stresses, owing to their high stiffness and resistance to crack propagation. Finally, the optimization of angular coverage revealed that a reinforcement sector of 45° provides nearly the same mechanical benefit as full coverage, thereby achieving an efficient balance between repair effectiveness and material consumption.

The main findings of this study can be summarized as follows:

- Crack propagation in the aluminum pipeline is governed by mode I, with K_1 consistently dominating over K_2 and K_3.
- The orientation of 0° is the most severe case and serves as the critical reference for optimization.
- Fiber alignment at 0° offers the maximum reduction in crack-driving stresses for all composites considered.
- Boron-based composite patches outperform carbon and glass counterparts in terms of reinforcement efficiency.
- An angular coverage of 45° is sufficient to ensure a reliable repair without unnecessary material usage.
- The optimal repair configuration consists of a boron patch, with fibers oriented at 0°, covering a 45° sector of the pipeline circumference.

This study confirms the relevance of a multi-parameter optimization strategy for developing robust and economical composite repairs for aluminum pipelines. It also demonstrates the effectiveness of numerical modeling in predicting structural behavior and guiding repair design prior to experimental implementation.

Future work could expand this framework by incorporating fatigue loading, adhesive aging, and environmental effects, as well as performing experimental validation on physical prototypes to further consolidate the numerical predictions.

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