Optimization of Composite Patch Repair for Cracked Aluminum Plates

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Abstract: This article presents a methodology for repairing cracked aluminum plates using composite patches. The study includes the definition of material properties, modeling with Abaqus, analysis of stress intensity factors, and optimization of patch dimensions and fiber orientation to improve repair efficiency.

Keywords: Aluminium, Crack, Composite patch, Optimization, Stress intensity, Abaqus

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1. INTRODUCTION

Metal structures, particularly in critical sectors such as aerospace, are subjected to demanding operational conditions that can lead to cracks and structural failures. Repairing these cracks is crucial to ensuring the safety and durability of structural components. In recent years, the use of composite patches to repair cracked metal plates has garnered increasing interest.

The selection of composite materials to repair corroded structural components in the offshore oil and gas sector has become common, requiring a meticulous process to choose the appropriate constituent elements. Numerical models are effective tools for understanding the impact of associated variables, identifying the causes of failures, and simulating failure propagation (Jiang et al., 2019; Breitzman & al., 2009). It's important to study the mechanical behavior of the adhesive layer at the steel-composite interface is essential, especially when repairing perforated tubular structures under various loads. A Python subroutine was developed to identify failure modes, highlighting that pure shear mode is the predominant in many repairs (Martinez & al., 2024).

Research has also explored the use of asymmetric hydrogel composites to repair defects in contaminated abdominal walls, demonstrating antibacterial properties and durable mechanical support. These composites promote tissue healing and reduce inflammation (Yu & al., 2024). Parallel studies on optimizing the shapes of composite repair patches in aerospace using strength analysis and digital image correlation (DIC) have provided more reliable bases for selecting optimal shapes (Xing & al., 2024).

Significant advances have been made in repairing massive rotator cuff tears (MRCT) using composite patches with improved mechanical properties and biocompatibility, showing promising results for enhancing repairs in animal models (Na & al., 2024). The effects of different stacking sequences of parent laminates and patches on the impact resistance of carbon fiber reinforced polymer (CFRP) composites have also been studied, revealing the effectiveness of adhesive patch repair methods (Kumar & al., 2024).

Several studies have explored the influence of fiber orientation in composite patches on various mechanical properties. For example, Jiang and al. demonstrated the importance of fiber orientation in predicting the perforation resistance behaviors of composite panels repaired with patches during impact. Other research focused on the effect of patch dimensions and fiber orientation on the buckling of hybrid composites (Erdem & al., 2021), as well as the impact of fiber orientation angle on the repair of composite plates (Kaman & Cetisli, 2021).

Studies have examined patch configurations and how the prestress affects stress intensity factors for inclined cracks in steel plates (El-Emam & al., 2017). The simultaneous optimization of topologies and fiber orientations in laminated composite structures has also been addressed (Lu & Tong, 2022). Galehdar and al (2011). emphasized the importance of fiber orientation on the performance of antennas integrated into carbon fiber composites. Zarrinzadeh and al (2017). analyzed crack growth and delamination in aluminum pipes that were repaired with composite patches during fatigue loading, highlighting practical durability.

The vibrational performance of composite plates that are reinforced with piezoelectric patches has been optimized (Niu & al., 2019). Nikbakt and al (2018). reviewed the optimization of composite structures, while Bhatia and Arockiarajan (2019) studied the fatigue of woven carbon composites that were repaired with patches. Analyses of the effects of fiber orientation and boundary conditions on the optimal placement of PZT sensors on composite structures have also been conducted (Samyal & al., 2021).

In summary, although significant progress has been made in understanding the mechanisms that govern the effectiveness of composite patches, gaps remain, particularly for bilateral repairs. This research aims to fill these gaps by systematically evaluating the impact of fiber orientation in composite patches for repairing cracked metal plates, focusing on bilateral configurations and cross-ply stackings [α, -α].

2. Problem Statement

The repair of cracked aluminum plates with composite patches is a growing field of research, particularly due to the stringent safety and durability requirements in critical sectors like aerospace and the offshore oil and gas industry. Despite significant advancements in understanding repair mechanisms, a persistent challenge is determining the optimal patch dimensions to ensure effective and durable repairs.

The choice of patch dimensions, including its length and width, plays a crucial role in stress distribution and the longevity of the repair. Inadequate patch dimensions can lead to uneven stress distribution, causing premature repair failure. Additionally, the interaction between patch dimensions and fiber orientation can affect the overall repair effectiveness. Therefore, determining the optimal dimensions is essential to ensuring durable and effective repairs.

Another critical aspect of composite patch repair is the choice of material. Three main materials are often considered for patches: boron, carbon, and glass. Each of these materials has unique characteristics that influence repair performance. For example, boron offers exceptional strength and performs well under high loads, while carbon is valued for its light weight and rigidity. Glass, on the other hand, is often chosen for its corrosion resistance and insulating properties. The selection of the optimal material depends on the specific repair requirements, such as the necessary mechanical strength, environmental conditions, and cost.

To address this issue, a methodical approach is necessary. First, it is essential to select the optimal material from boron, carbon, and glass. This selection will be based on a comparative evaluation of stress intensity factors and the mechanical performance of the materials under different loading conditions. Once the optimal material is identified, the optimal patch dimensions can be determined.

The main objective of this research is to develop a numerical model to systematically evaluate the performance of patches of different dimensions under various loading conditions. This model will consider the interactions between patch dimensions, fiber orientation, and the properties of the selected material. Crack propagation simulations and stress distribution analyses will be performed to identify dimensions that minimize stress intensity factors and maximize repair durability.

Furthermore, this research will examine how optimal dimensions vary according to specific operational conditions, such as temperature variations and cyclic loads. By combining numerical analyses with experimental tests, this study aims to provide precise and applicable recommendations for selecting patch dimensions in real industrial applications.

3. Methodology

3.1. Design and Modeling of the Aluminum Plate

3.1.1. Definition of Material Properties

The first step is to define the material properties of the aluminum plate to be repaired. The plate is in 200 mm × 100 mm × 2 mm in size. the table below shows the mechanical properties of the aluminum used in this study .

Table 1: Mechanical Properties (Isotropic) of the Plate

Young's Modulus	Poisson's Ratio
72000	0.3

These properties will serve as the basis for evaluating the effectiveness of the composite patch repair.

3.1.2. Geometric Modeling

We use Abaqus software to model the geometry of the cracked plate. Figure 1 illustrates the geometric model of the aluminum plate. Special attention is given to accurately representing the crack.

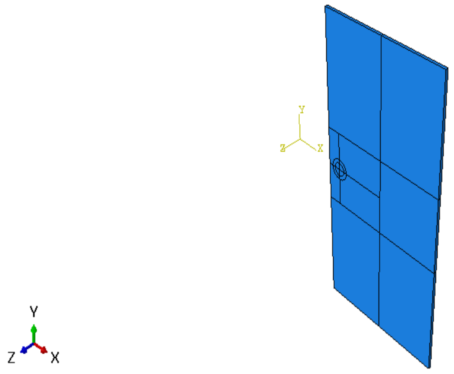

Figure 1. The geometric model of the aluminum plate

3.1.3. Application of Load

In our simulation, we applied a fixed boundary condition at one end of the plate to hold it in place. Subsequently, a displacement force is applied along the Y-axis at the other end of the plate. This loading configuration is crucial for observing and analyzing stress behaviors in the cracked plate, facilitating the evaluation of the effectiveness of various patch configurations in subsequent simulations. Figure 2 illustrates the applied loads.

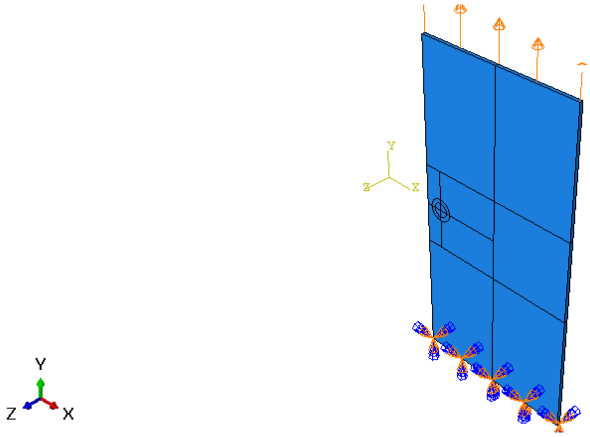

Figure 2. Illustration explaining the applied loads on the plate.

3.1.4. Analysis of Stress Intensity Factors

We conduct an initial analysis to observe the mode I (K1), mode II (K2), and mode III (K3) stress intensity factors for the cracked plate without a patch. This allows us to understand the nature of the crack and the dominant stress modes. The results of this analysis will guide the design and application of the composite patch.

3.2. Patch Selection and Assembly with the Plate

3.2.1. Selection of Composite Materials

Three composite materials are considered for the repair: boron, carbon, and glass. The mechanical properties of these materials are presented in the following tables. Based on the results of our analyses, we will choose the most suitable material for our simulation.

Table 2. Mechanical Properties of Boron Patch

E1	E2	v12	G12	G13	G23
211000	21400	0.36	6900	6900	6900

Table 3. Mechanical Properties of Glass Patch

E1	E2	v12	G12	G13	G23
45000	10000	0.3	5000	5000	3846.5

Table 4. Mechanical Properties of Carbon Patch

E1	E2	v12	G12	G13	G23
121000	8600	0.27	4700	4700	3100

3.2.2. Geometric Modeling of the Patch

Figure 3 depicts the geometric model of the composite patch. We design the patch with the aim of minimizing the stress intensity factor and effectively repairing the aluminum plate.

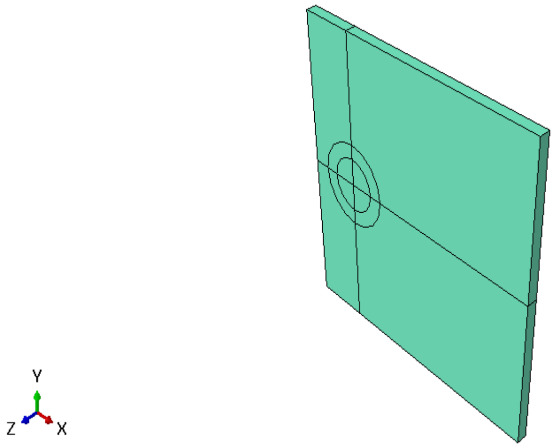

Figure 3. The geometric model of the Patch

3.2.3. Assembly of the Patch and Plate

Figure 4 illustrates the assembly of the plate and the patch. We use the FM300 adhesive, known for its high strength and durability, to bond the patch to the aluminum plate. The properties of the adhesive are provided in the table below:

Table 5 Mechanical Properties of Adhesive

Young's Modulus	Poisson's Ratio
2450	0.38

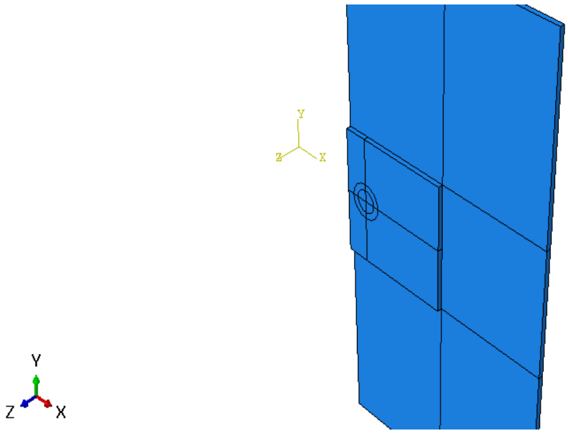

Figure 4. Assembly of the plate and patch

3.3. Optimization of Patch Dimensions with Fiber Orientation by Cross-Stacking

The detailed methodology for optimizing patch dimensions with fiber orientation by cross-stacking is crucial to ensure effective repair of cracked aluminum plates. The simulation procedure unfolds in several stages, each aimed at identifying and validating optimal configurations of the composite patch.

3.3.1. Simulation Procedure

a. Initial Simulation

The first step involves conducting an initial simulation without the patch. This simulation is pivotal for establishing a baseline stress distribution and identifying critical stress points on the cracked aluminum plate. By conducting this initial simulation, we gain a better understanding of the nature and extent of stresses in the unrepaired plate. This provides a comparison point to evaluate the effectiveness of different patch configurations in subsequent simulations.

b. Application of the Composite Patch

Following the initial simulation, we apply the composite patch to the cracked area of the aluminum plate. This step involves accurately modeling the patch over the crack and defining the material properties of the composite in the simulation software. We then rerun the simulation to observe changes in stress distribution caused by the patch application. This step evaluates the immediate impact of the patch on reducing stresses at the crack site.

c. Parametric Study

The parametric study constitutes a key phase of optimization. In this step, we systematically vary the dimensions and orientations of the patch to identify the optimal configuration that minimizes stress intensity factors (K1, K2, K3). By altering patch dimensions and adjusting fiber orientations, we can determine combinations that offer the best repair performance.

3.3.2. Optimization of Patch Dimensions

Once the appropriate material is selected through comparative study of a 50 mm × 50 mm patch, we proceed with optimizing patch dimensions. This process is divided into two parts: height optimization and width optimization.

a. Height Optimization

To optimize patch height, we set the width to 50 mm and incrementally increase the height by 25 mm up to 200 mm. Tested configurations include: 50 mm × 50 mm, 75 mm × 50 mm, 100 mm × 50 mm, 125 mm × 50 mm, 150 mm × 50 mm, 175 mm × 50 mm, and 200 mm × 50 mm. Each configuration is simulated to observe how varying height affects stress distribution and stress intensity factors. This approach helps determine the optimal height that minimizes stresses at the crack site.

b. Width Optimization

After determining the optimal height, we fix this height and incrementally increase the width by 12.5 mm up to 100 mm. Tested configurations include: Optimal Height × 50 mm, Optimal Height × 62.5 mm, Optimal Height × 75 mm, Optimal Height × 87.5 mm, and Optimal Height × 100 mm. Each configuration is analyzed to assess how patch width impacts repair performance. This width optimization phase aims to fine-tune patch dimensions for maximum effectiveness.

3.3.3. Fiber Orientation

Fiber orientation in the composite patch is a critical factor influencing repair performance. In each simulation, we vary fiber layer orientations from 0° to 90° in a cross-stacking sequence. This method identifies the optimal fiber orientation that maximizes the patch's ability to reduce stresses at the crack site. Fiber orientations are adjusted to best exploit the anisotropic properties of composite materials, thereby enhancing overall repair efficiency.

4. Results and Discussions

4.1. Crack Mode: Mode I

4.1.1. Comparative Graph of Stress Intensity Factors

The initial analysis of stress intensity factors (K) allowed us to determine the predominant crack mode in the cracked aluminum plate. Stress intensity factors K1, K2, and K3 were calculated for the plate without the patch. The results showed that the stress intensity factor of Mode I (K1) is significantly higher than Mode II (K2) and Mode III (K3), indicating that the crack is primarily governed by an opening mode (Mode I). This conclusion is supported by the comparative graph below, where K1 notably exceeds K2 and K3 across different crack lengths.

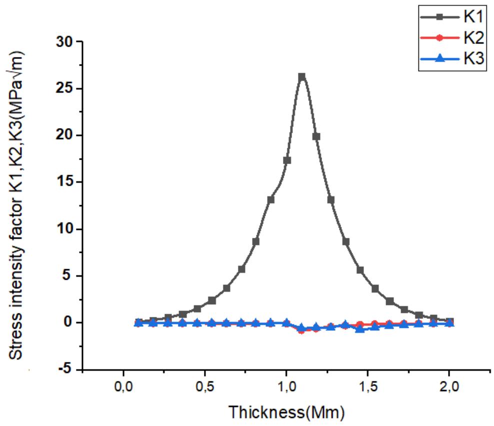

Figure 5. Comparison of the different stress intensity factors

4.1.2. Crack Visualization

The visualization of the crack in the aluminum plate, conducted using Abaqus software, clearly shows the propagation of the crack under the influence of applied stresses. The figure below illustrates the crack and the areas of maximum stress concentration, providing a clear picture of the structural challenges to be addressed for repair.

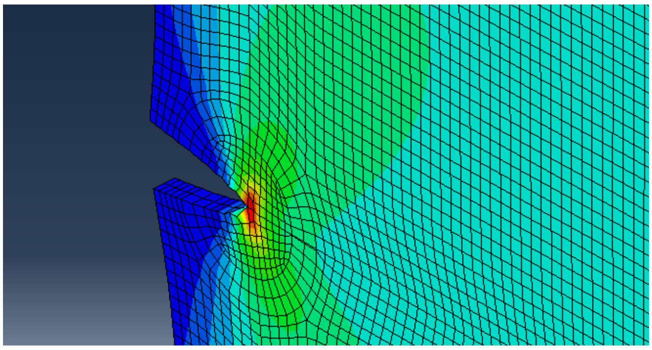

Figure 6. Visualization of the crack on the plate

4.2. Material Selection

4.2.1. Comparison of Stress Intensity Factors for Different Materials

Three composite materials were considered for repairing the cracked plate: boron, carbon, and glass. The mechanical properties of these materials were presented earlier. To evaluate their effectiveness, we compared the stress intensity factors (K) for each material. Results showed that boron material offers the best results, with significantly reduced stress intensity factors compared to carbon and glass, as shown in the following graph comparing the three materials at a fiber orientation of 90°.

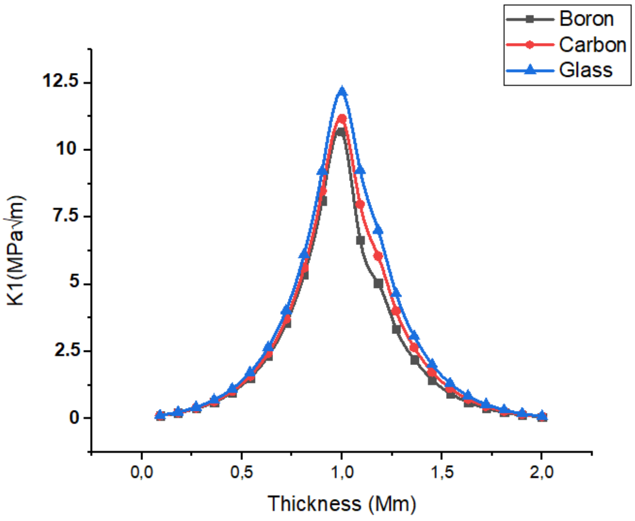

Figure 7. Comparative graph of stress intensity factors for the 3 materials

4.2.2. Fiber Orientation Analysis for Boron

A parametric study was conducted to analyze the impact of fiber orientation on the effectiveness of the boron patch. Eleven different orientations, ranging from 0° to 90°, were simulated. The results indicate that the fiber orientation at 90° provides the greatest reduction in stress intensity factors. The graph below compares the K values for the different fiber orientations.

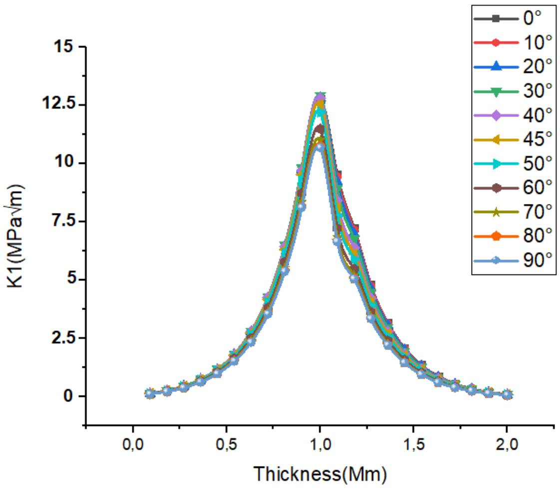

Figure 8. Comparative graph of the 11 fiber orientations for boron

4.3. Patch Dimension Optimization

4.3.1. Height Optimization

To optimize the patch dimensions, we initially fixed the patch width at 50 mm and varied the height from 50 mm to 200 mm in 25 mm increments. Simulations showed that the optimal height of the patch is 200 mm, providing the greatest reduction in stress intensity factors. The graph below illustrates the comparison of tested heights at a fiber orientation of 90°.

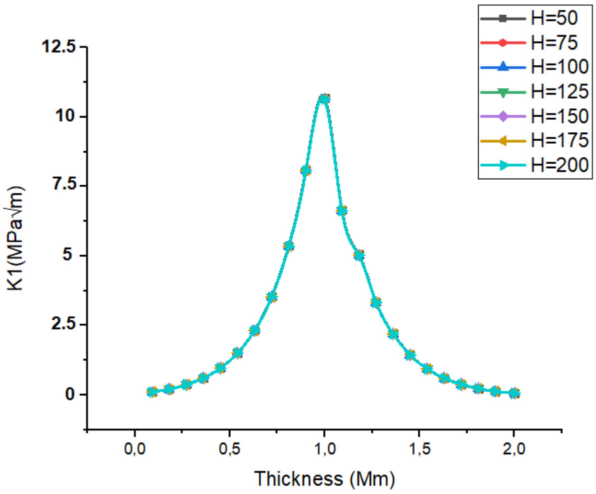

Figure 9. Comparative graph after varying the height

4.3.2. Width Optimization

After determining the optimal height of 200 mm, we proceeded to optimize the width of the patch. Keeping the height at 200 mm, we varied the width from 50 mm to 100 mm in 12.5 mm increments. Results indicated that the optimal width remains at 50 mm, as increasing the width did not significantly improve the stress intensity factors. The following graph compares the different widths tested at a fiber orientation of 90°.

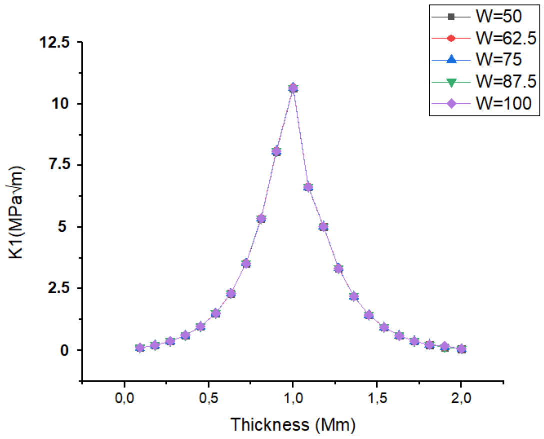

Figure 10. Comparative graph after varying the width

4.3.3. Fiber Orientation Optimization

To finalize the optimization, we conducted simulations adjusting the fiber orientation for all patch dimensions, particularly focusing on the optimal dimension of 200 mm x 50 mm. Results confirmed that the 90° angle provides the best performance in terms of reducing stress intensity factors. The graph below compares results for the 11 fiber orientations, demonstrating that this optimal orientation was systematically evaluated for each dimension to ensure consistent and reliable outcomes.

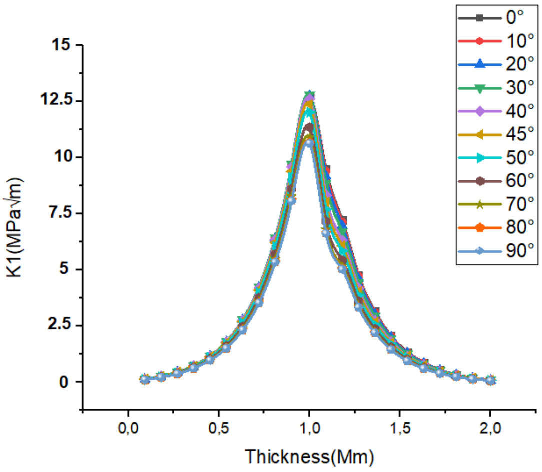

Figure 11. Comparative graph after varying fiber orientation

5. Conclusion

This study explored the optimization of repairing cracked aluminum plates using composite patches, exclusively through simulations using ABAQUS software. The main objective was to determine the optimal configurations of composite patches to minimize stress intensity factors and strengthen damaged plates.

The simulation results demonstrated that the choice of patch material, optimal dimensions, and fiber orientation play crucial roles in repair effectiveness. Among the materials studied, the boron patch emerged as the most effective, surpassing carbon and glass in terms of reducing stress intensity factors. This choice was confirmed through rigorous comparative analysis of simulations, which consistently showed superior results with boron, particularly with a fiber orientation of 90°.

The optimization of patch dimensions was conducted in two stages. First, patch height was optimized by fixing the width at 50 mm and incrementally increasing the height from 50 mm to 200 mm. Simulation results indicated that the optimal height was 200 mm, providing the best stress reduction. Second, patch width was optimized by fixing the optimal height and incrementally increasing the width from 50 mm to 100 mm in 12.5 mm increments. The optimal width was determined to be 50 mm, even after testing larger widths in simulations.

Fiber orientation within the composite patch was also critical. Simulations revealed that the 90° angle offered the best performance in terms of reducing stress intensity factors. This orientation effectively dispersed stresses and minimized crack propagation, highlighting the importance of precise fiber alignment to maximize patch effectiveness.

Final simulations confirmed the effectiveness of optimized configurations, demonstrating significant improvement in the structural integrity of repaired aluminum plates. These results underscore the importance of a methodical and systematic approach to optimizing composite patch repairs.

This study provides a significant contribution to the understanding and optimization of repairs for cracked aluminum plates using composite patches, based on simulations conducted with ABAQUS software. Simulation results underscore that material choice, patch dimensions, and fiber orientation are crucial for ensuring effective and durable repairs. This methodology can be applied to other types of cracked structures, providing a framework for optimized repairs across various industrial domains.

The significance of this study lies not only in its simulated outcomes but also in the detailed methodology that can be replicated and adapted for other applications. Future research could explore additional composite materials, patch configurations, and simulation techniques to further enhance repair solutions for aluminum and similar materials. This study thus lays the groundwork for further advancements in composite material repair, contributing to safer, more durable, and higher-performing structures.

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