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Research Paper

Investigating Crack Growth Behavior in Alu-Bond Composite Sheets and Repairing with Composite Patch Connections

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Abstract
This study investigates using composite patch connections to repair cracked composite sheets under tensile stress. Finite element analysis was employed to model and analyze the behavior of the cracked composite sheet in three scenarios: without a patch, with a one-sided patch, and with a two-sided (symmetric) patch. The primary objective was to examine the influence of the composite patch material on the stress distribution, crack growth strain, and overall performance of the repaired sheet. An optimization approach was also developed to design the multilayer composite patch connection with the lowest weight and cost while withstanding the highest possible load. Two optimization algorithms, the Genetic Algorithm and the Colonial Competitive Algorithm, were implemented and compared in this regard. The results demonstrate that using a symmetric, two-sided composite patch connection effectively reduces crack growth and enhances the strength of the repaired sheet.
Furthermore, the optimization analysis revealed that the Colonial Competitive Algorithm provided superior performance to the Genetic Algorithm in identifying the optimal design parameters for the composite patch connection. This study contributes to understanding crack behavior in composite sheets and developing cost-effective, weight-efficient repair solutions using composite patch connections. The findings can inform the design and implementation of composite repair techniques in various engineering applications.

Keywords
Composite Sheet, Crack Repair, Composite Patch Connection, Genetic Algorithm (GA), Colonial Competitive Algorithm (CCA)

1. Introduction

Repairing cracked metal sheets is a critical challenge in many engineering applications, as it is essential to restore the structural integrity and extend the service life of these components. Various strengthening methods have been explored to address this issue, with composite patch connections emerging as one of the most widely adopted approaches. In the composite patch repair technique, layers of composite materials are bonded to the cracked sheet, either on a single side (asymmetric configuration) or on both sides (symmetric configuration), when access to the sheet is available on both surfaces. The composite patches are designed to bear a significant portion of the load applied to the cracked sheet, effectively preventing the further propagation of the crack under both static and fatigue loading conditions [1].

There are numerous advantages to using composite patches for repair. Firstly, the composite materials can increase the strength of the repaired structure without drilling or riveting, which can compromise the structural integrity. Additionally, composite patches offer a weight-efficient solution compared to traditional metal-based repair methods, as they can provide enhanced strength-to-weight ratios. The flexibility in designing and arranging the composite layers also allows for repairing irregularly shaped components, which is a significant benefit in many engineering applications [2].

Moreover, composite materials exhibit excellent fatigue and corrosion resistance, making them well-suited for applications where the repaired structure is subjected to cyclic loads or harsh environmental conditions. Finally, composite patch repairs can save costs by reducing the need for extensive component replacement or complex machining operations. It is important to note, however, that the installation time and process complexity associated with composite patch repairs should also be considered when evaluating the suitability of this approach for a particular application [3].

In recent years, a growing body of research has been dedicated to investigating the effects of composite patch connections on the static and fatigue behavior of cracked composite sheets. These studies have been conducted through a combination of laboratory experiments and numerical analyses, providing valuable insights into the performance of this repair technique [4]. The research efforts in this area have focused on various aspects of the composite patch repair process. Experimental studies have been carried out to assess the crack growth behavior and the load-bearing capacity of cracked composite sheets repaired with composite patches under static and cyclic loading conditions. These laboratory investigations have used advanced measurement techniques and instrumentation to capture the detailed mechanical response of the repaired structures [5].

Complementing the experimental work, numerical modeling and simulation approaches, such as finite element analysis, have been employed to understand further the underlying mechanisms and stress distributions within the cracked composite sheets and the composite patch connections. These computational studies have enabled researchers to explore a wider range of design parameters, material properties, and loading scenarios, which can be challenging to replicate in physical experiments. The findings from these research endeavors have been crucial in advancing the understanding of the effectiveness of composite patch repairs in mitigating crack growth and enhancing the durability of cracked composite structures. The insights gained from these investigations have informed the development of design guidelines, optimization strategies, and practical implementation procedures for composite patch repair solutions in various engineering applications [6].

The use of genetic and colonial competition algorithms has allowed for the exploration of a wider design space, leading to the identification of composite amplifier configurations that offer enhanced weight-to-strength ratios and reduced manufacturing costs. By leveraging the inherent capabilities of these meta-heuristic methods to handle complex, multi-objective optimization problems, the research has aimed to deliver optimized composite amplifier solutions that can significantly benefit weight reduction, structural integrity, and overall cost-effectiveness [7]. The comparative analysis conducted within the Abaqus software environment has provided valuable insights into the performance characteristics of the amplifiers obtained through the different optimization approaches. This comprehensive evaluation has enabled the researchers to make informed decisions on the most suitable composite amplifier design for the specific application requirements, ultimately contributing to the advancement of lightweight and cost-effective composite structures [8].

This research investigates the effect of one-sided and two-sided composite reinforcement on the stress intensity factor, which predicts crack growth. Numerically, the Paris law equation was used, which was coded in MATLAB software for ease of computation, and the values were obtained from the Abaqus finite element software. The analysis was conducted for reinforcement materials consisting of glass-epoxy, graphite-epoxy, and boron-epoxy, each with four layers. The one-way and two-way reinforcement cases were studied separately, and the results were compared. Meta-heuristic optimization algorithms have improved and optimized the composite amplifier's weight, strength, and total cost. Specifically, the genetic algorithm method and the colonial competition algorithm have been utilized to design and analyze the composite amplifiers. The performance of the amplifiers obtained from these optimization techniques has been evaluated separately using the finite element software. The results from the optimized amplifiers have been compared against other conventional amplifier designs to assess the improvements achieved by applying these meta-innovative algorithms.

2. Formulation of the Problem

2.1 Failure in Biaxial Mode for Orthotropic Material

The Tsai-Wu failure criterion governs the stress state within the layers of the orthotropic material. This tensor-based relationship is used to determine the onset of failure. Once a layer reaches the failure condition, it is removed from the total number of layers in the composite structure [9]. The mathematical expression of the Tsai-Wu failure criterion is:

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j = 1 \qquad (1)$$

Where i, j are the tensor indices and F_i, F_{ij} are the second and fourth-order strength tensors. If we have:

$$\sigma_6 = \tau_{12}, \sigma_5 = \tau_{31}, \sigma_4 = \tau_{23} \qquad (2)$$

As a result, the above relationship for the plane stress state is as follows:

$$F_1\sigma_1 + F_2\sigma_2 + F_6\sigma_6 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 = 1 \qquad (3)$$

The Tsai-Wu failure coefficients F_i and F_{ij} can be expressed in terms of the material's principal strength properties, namely the tensile and compressive strengths in the three orthogonal directions. For the case where stresses are applied in the principal direction 1, the Tsai-Wu coefficients can be written as:

$$\begin{gathered} F_1X_t + F_{11}X_t^2 = 1 \\ F_1X_c + F_{11}X_c^2 = 1 \\ F_1 = \frac{1}{X_t} + \frac{1}{X_c} \quad , \quad F_{11} = -\frac{1}{X_tX_c} \end{gathered} \qquad (4)$$

X_t is the tensile strength in direction 1, and X_c is the compressive strength in direction 1. In the case where the stresses are applied in the principal direction 2, the Tsai-Wu failure coefficients can be expressed as:

$$F_2 = \frac{1}{Y_t} + \frac{1}{Y_c} \quad , \quad F_{22} = -\frac{1}{Y_t Y_c} \tag{5}$$

Y_t is the tensile strength in direction 2, and Y_c is the compressive strength in direction 2. This formulation allows the Tsai-Wu failure criterion to be tailored to the specific strength properties of the orthotropic composite material in the principal direction 2. By considering both the tension and compression states, the model can accurately capture the asymmetric behavior of the material under different loading conditions. Defining the Tsai-Wu coefficients using the principal strength values is crucial for the reliable assessment of failure in orthotropic composites, as it directly incorporates the material's anisotropic characteristics into the failure analysis.

For the Tsai-Wu coefficient F_{12}, which represents the interaction between the principal stresses, a formula can be derived based on the previously defined relationships. The expression for F_{12} can be obtained as:

$$F_{12} = \frac{1}{2\sigma^2}\left[1 - \left(\frac{1}{X_t} + \frac{1}{X_c} + \frac{1}{Y_t} + \frac{1}{Y_c}\right)\sigma + \left(\frac{1}{X_t X_c} + \frac{1}{Y_t Y_c}\right)\sigma^2\right] \tag{6}$$

This formula considers the tensile and compressive strengths in the two principal directions, X_t, X_c, Y_t, and Y_c, to capture the coupling effect between the stresses in the orthotropic material. Including F_{12} in the Tsai-Wu failure criterion is essential, as it allows for accurately modeling the interaction between the principal stresses. This is particularly important for composite materials, where the failure behavior is often influenced by the combined effect of stresses in multiple directions. By incorporating this formulation for F_{12}, the Tsai-Wu failure criterion becomes a comprehensive tool for predicting the onset of failure in orthotropic composite structures under complex, multiaxial stress states. This enhanced capability is crucial for the reliable design and analysis of advanced composite materials and structures.

2.2 Multilayer Forces and Moments

In a multi-layered composite plate, the resultant forces and moments acting on the structure can be calculated by integrating the stresses across the thickness of the individual layers. This integration process allows for determining the overall force and moment resultants acting on the composite plate. The mathematical representation of the force and moment resultants can be written as:

$$\begin{Bmatrix} N_X \\ N_Y \\ N_{XY} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix} dz \tag{7}$$

$$\begin{Bmatrix} M_X \\ M_Y \\ M_{XY} \end{Bmatrix} = \int_{-t/2}^{t/2} \begin{Bmatrix} \sigma_X \\ \sigma_Y \\ \tau_{XY} \end{Bmatrix} zdz \tag{8}$$

Nx, Ny, and Nz represent the force resultant in the *X*, *Y*, and *Z* directions. Also, M_x, M_y, and M_z represent the moment resultant about the X, Y, and Z axes. *z* is the coordinate through the thickness of the plate, and *h* is the total thickness of the multi-layered composite plate, which can be seen in Figure 2, showing the layers of the sample sheet. By performing this integration, the overall force and moment resultants experienced by the multi-layered composite plate can be determined. This information is crucial for the structural analysis and design of composite structures, as it allows for evaluating the load-bearing capacity and identifying potential failure modes. Figure 1 shows the forces and moments of a flat multilayer. The integration of the stresses across the thickness of the individual layers captures the contribution of each layer to the overall force and moment resultants, accounting for the anisotropic and heterogeneous nature of the composite material.

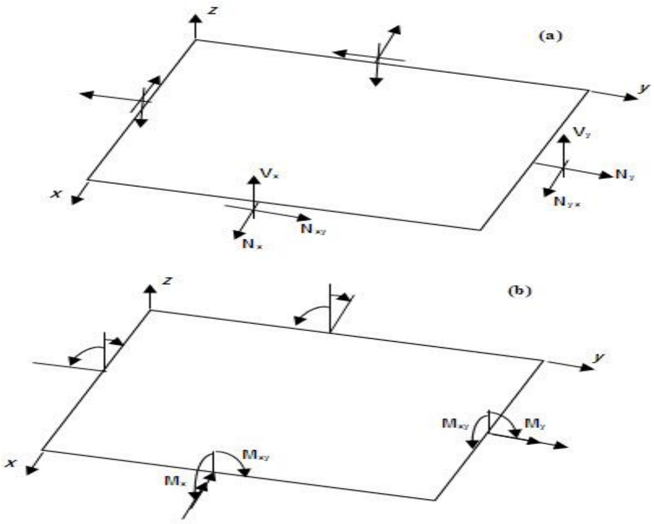

Figure 1. Forces and moments of a flat multi-layered composite plate

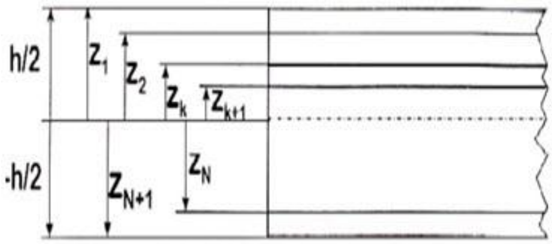

Figure 2. Layers of the sample composite plate

The force and moment resultants expressed in the previous equations can be further organized and summarized as follows:

$$N_i = \sum_{k=1}^{n} A_{ij\in_j^0} + \sum_{k=1}^{n} B_{ij}K_j \qquad (9)$$

$$M_i = \sum_{k=1}^{n} B_{ij\in_j^0} + \sum_{k=1}^{n} D_{ij}K_j \qquad (10)$$

Where A_{ij} are the elements of the in-plane stiffness matrix, also known as the tensile stiffness, B_{ij} are the elements of the coupling stiffness matrix, which represent the coupling between in-plane and bending deformations, D_{ij} are the elements of the bending stiffness matrix, which govern the bending behavior of the multi-layered composite plate. These stiffness matrices, A_{ij}, B_{ij}, and D_{ij}, are collectively called the Classical Laminate Theory (CLT) stiffness parameters. They are fundamental to the analysis and design of multi-layered composite structures, as they capture the overall mechanical response of the composite plate under various loading conditions.

The tensile stiffness A_{ij} represents the in-plane load-bearing capacity of the composite plate, the coupling stiffness B_{ij} accounts for the interaction between in-plane and bending deformations, and the bending stiffness D_{ij} governs the plate's resistance to bending loads.

2.3 Crack Growth Rate Analysis

The Paris law equation is commonly used to analyze the crack growth rate. The Paris law relates the stress intensity factor to the crack growth under fatigue stress. The crack growth equation based on the Paris law is defined as follows:

$$\frac{dS}{dN} = G\Delta K^{j} \tag{11}$$

On the right side of the equation, G and j are the material-dependent constants determined experimentally. ΔK represents the range of the stress intensity factor, which is the difference between the maximum and minimum stress intensity factors during a fatigue cycle. In the crack growth equation, S represents the length of the crack, and N represents the number of load cycles. The left side of the equation, dS/dN, is known as the crack growth rate, which means the infinitesimal change in crack length over an increasing number of load cycles. The stress intensity factor ΔK is obtained from the following equation:

$$\Delta K = \Delta\sigma Y\sqrt{\pi S} \tag{12}$$

Y is a dimensionless factor that depends on the component's geometry and the crack, σ is the applied stress range, and S is the crack length. The factor Y can be considered independent of the crack length S for relatively short cracks. In this case, the crack growth equation can be solved through the separation of variables:

$$\int_0^{N_f} dN = \int_{S_i}^{S_c} \frac{dS}{G(\Delta\sigma Y\sqrt{\pi S})^j} = \frac{1}{G(\Delta\sigma Y\sqrt{\pi})^j}\int_{S_i}^{S_c} S^{-\frac{j}{2}} ds \tag{13}$$

Integrating this equation yields the following relation:

$$N_f = \frac{2\left(S^{\frac{2-j}{2}} - S_i^{\frac{2-j}{2}}\right)}{(2-j)G\left(\Delta\sigma Y\sqrt{\pi}\right)^j} \tag{14}$$

Where N_f is the number of remaining cycles to failure, S_c is the critical crack length where instantaneous failure occurs, S_i is the initial crack length where crack fatigue growth begins, $\Delta\sigma$ is the stress range, and Y is a value between 0 and 1, depending on the crack size S_i. The Paris law equation is widely used in fracture mechanics to predict the crack growth behavior and the remaining life of a component under fatigue loading. By applying this equation, engineers can estimate the crack growth rate and plan appropriate maintenance or replacement strategies to ensure the structural integrity and safety of the component.

2.4 Colonial Competition Algorithm

The Colonial Competition Algorithm (CCA) is a metaheuristic optimization technique used to solve various complex optimization problems in computer science. Like many other nature-inspired algorithms, the CCA does not require calculating gradient information during optimization. Algorithms inspired by natural phenomena have shown promising results as efficient optimization methods, complementing classical mathematical optimization techniques. Some well-known examples include Genetic Algorithms (GA), which are inspired by the biological evolution of living organisms, and Ant Colony Optimization (ACO), which is based on the observed foraging behavior of ants. The Colonial Competition Algorithm is inspired by the socio-political phenomenon of colonization and the competition between colonial powers. The algorithm mimics the process of a colonial power establishing colonies, competing with other colonial powers, eventually leading to the dominance of the most influential colonial empire. This algorithmic approach has successfully solved many optimization problems since its introduction in the early 2000s [10- 11].

The key steps of the CCA include the initialization of a population of countries (solutions), the establishment of colonies by the most powerful countries (elite solutions), the competition between colonial powers to expand their influence, and the gradual convergence towards the most dominant colonial empire (the global optimum solution). Through this iterative process, the CCA can explore the search space effectively and identify high-quality solutions to the optimization problem.

This section investigates three objectives for optimizing composite plates: minimizing weight, minimizing cost, and maximizing final load. The weight of the sheet can be calculated using the following relationship:

$$M = a.b(\rho_1 t_1 + \rho_2 t_2 + \cdots + \rho_n t_n) \qquad (15)$$

Where M represents the weight of the sheet, and (a, b) denotes the length and width of the sheet. Additionally, (ρ_n) stands for the density of the nth layer, while (t_n) indicates the thickness of the n_{th} layer; calculating the cost of a sheet involves two key factors: the material cost per layer and the cost associated with the fiber orientation, as manufacturers assign varying prices for different fiber directions. Let Cc and the manufacturing cost by Cm denote the composite material cost. The total cost of the sheet (C_t) can be expressed as:

$$C_c = \sum_{k=1}^{n} C_{fk} \qquad (16)$$

$$C_m = \sum_{k=1}^{n} C_{fk}$$
$$C_t = C_c + C_m$$

In this context, C_f represents the cost of each layer. The ultimate breaking load value is determined through the analysis program, with the load at which the final layer fails serving as the criterion. For this study, the load is applied in the N_x direction on the composite sheet. The objective function for the breaking load of N_x is derived based on the global criterion.

$$\varphi_3 = \left(2\frac{N_x}{N_x^*}\right)^2 \quad (17)$$

In this context, N_x^* represents the predetermined maximum load value consistent across all models. Consequently, the objective function is defined as the unrestricted multi-objective function outlined below:

$$f = \varphi_1 + \varphi_2 + \varphi_3 \quad (18)$$

The objective function f is employed to optimize weight, cost, and final load. The functions φ_1 and φ_2 are defined as follows:

$$\varphi_1 = \left(1 + \frac{M}{M^*}\right)^2$$
$$\varphi_2 = \left(1 + \frac{C}{C^*}\right)^2 \quad (19)$$

In the relationships mentioned above, M and C represent the weight and cost of each model, while M^* and C^* denote their maximum values, which are consistent across all designs. It is evident that as weight and cost decrease, the values of φ_1 and φ_2 also decrease, aligning with the objectives outlined in this article. The design variables in question are the unknown quantities that must be determined to optimize the objective function. These variables include thickness, fiber angle, and material for each layer. This study utilizes a 4-layer sheet, with specified ranges for fiber angles and layer thicknesses considered as follows:

$$-90 \le \theta \le 90 \quad (20)$$
$$0.075mm \le t \le 0.3mm$$

The fiber angle and thickness are not arbitrary values, as industry standards dictate specific angles and thicknesses for each layer. Each layer uses standard angles and thicknesses to ensure consistency and performance. Additionally, the sheet is designed to be a hybrid multilayer, with each layer being made of a different material. This study considered three materials: graphite-epoxy, glass-epoxy, and boron-epoxy. The specifications for these materials can be found in Table 1.

Table 1. Cost values for different angles

θ	C	θ	C
0	0.035	±60	0.039
±15	0.0375	±75	0.036
±30	0.0395	90	0.0355
±45	0.04		

3. Modeling

3.1 Geometric Characteristics of Samples

This research focuses on examining the damage caused in a composite sheet, specifically the presence of a crack, to find the optimal solution for its repair. Allobond Company manufactures the composite sheet used in this study, which has a rectangular shape with 1216 mm and 608 mm dimensions. To investigate the behavior of the composite sheet, the length and width dimensions have been reduced in equal proportion. The overall thickness of the composite sheet is 4.2 mm, where the thickness of the polyethylene layer is 3 mm, the aluminum layer is 0.5 mm, and the adhesive layer is 0.1 mm. A crack has been intentionally created at the center of one side of the composite sheet, with a length of 76 mm. The load applied to the sheet is in the form of tensile stress, which will be increased to 100 MPa. Figure 3 shows the crack created in the sample composite sheet. This loading condition is designed to simulate real-world scenarios where the composite sheet may experience mechanical stresses during its service life.

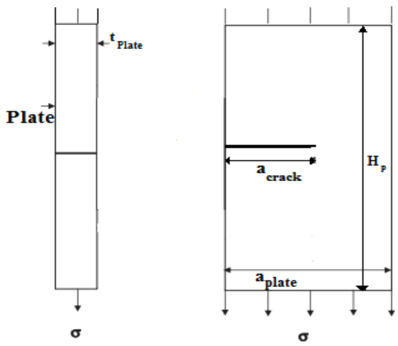

Figure 3. Crack propagation in the composite sheet

For the repair, a rectangular composite patch (as shown in Figure 4) will be placed on the crack on one side of the structure. The dimensions of the patch are H_{patch} = 152 mm and W_{patch} = 76 mm. The composite patch will comprise four symmetrical layers, each with a thickness of 0.15 mm. The fiber orientations of the layers will be [0°/90°/90°/0°]. Three different composite materials will be used to fabricate the patch samples separately: glass epoxy, boron epoxy, and graphite epoxy.

The performance of each of these three composite patch materials will be analyzed and compared. The analysis will evaluate the mechanical properties, durability, and effectiveness of repairing the crack. This comparative study will help determine the most suitable composite material for the repair application, considering strength, weight, and cost-effectiveness factors. Compared to a single-layer or randomly oriented patch, a multi-layered composite patch with carefully selected fiber orientations is expected to provide enhanced load-bearing capacity and crack-arresting capabilities. Analyzing the three different composite materials will provide valuable insights into the optimal choice for the specific repair requirement.

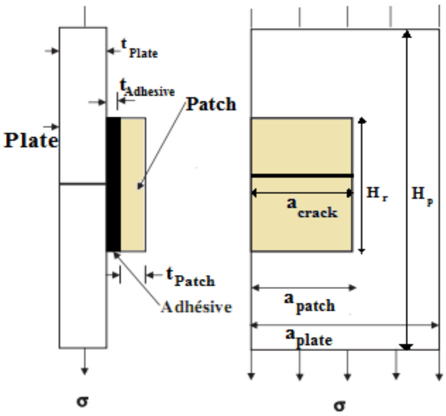

Figure 4. Use of a one-sided composite patch for repair

A rectangular composite patch (as shown in Figure 5) will be used for the repair, which will be symmetrically placed on the crack. The dimensions of the patch are H_{patch} = 152 mm and W_{patch} = 76 mm.

The composite patch will comprise four symmetrical layers, each with a thickness of 0.15 mm. The fiber orientations of the layers will be [0°/90°/90°/0°]. Three different composite materials will be used to fabricate the patch samples separately: glass epoxy, boron epoxy, and graphite epoxy.

In the optimization part of the study, additional composite patch designs will be explored using genetic algorithm and colonial competition algorithm optimization techniques. The optimized patches will be four layers, which can be a combination of materials (boron-epoxy, glass-epoxy, graphite-epoxy) with fiber angles ranging from -90° to 90°. The thickness of each layer will be allowed to vary from 0.1 mm to 0.3 mm. The optimization aims to determine the optimal combination of materials, fiber orientations, and layer thicknesses that can further enhance the load-bearing capacity, crack-arresting capabilities, and overall performance of the composite patch. The results of the optimization study will be compared with the initial three-material patch designs to identify the most effective solution for the repair application.

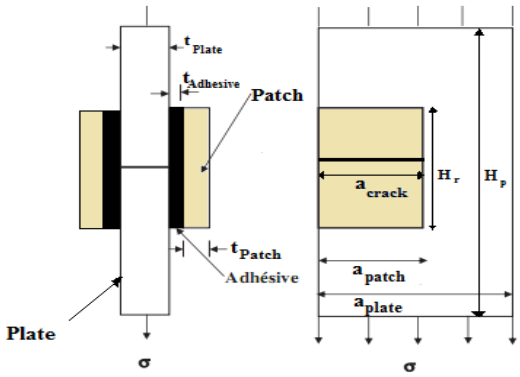

Figure 5. Use of double-sided composite patch for repair

3.2 Material Specifications

The material specifications for the composite sheet and composite patches used in this research were obtained from the composite sheet production company Alupond. The composite sheet is the primary material, while the epoxy-based composite patches are commonly used for repair and reinforcement. Tables 2 and 3 provide detailed specifications for the sample composite sheet and the composite patches utilized in the study. The composite sheet specifications include information about the material composition, physical properties, and performance characteristics. Similarly, the composite patch specifications outline the epoxy-based repair patches' composition, dimensions, and other relevant details. Similarly, Table 2 summarizes the specifications of the composite patches in the Tsai-Wu criterion.

Understanding the material properties of the composite sheet and the composite patches is crucial for evaluating their performance and suitability for the intended applications. The comprehensive material specifications presented in the subsequent tables will enable a thorough analysis of the components used in the research.

Table 2. Specifications of the composite patches in the Tsai-Wu criterion

	Glass - Epoxy	Born-Epoxy	Grafit-proxy
X_t (Mpa)	1000	1300	1500
X_C (Mpa)	-600	-2000	-1250
Y_t (Mpa)	30	70	50
Y_C (Mpa)	-120	-300	-200
S (Mpa)	70	80	100

Table 3. Specifications of the composite sheet components

	Glass - Epoxy	**Born-Epoxy**	**Grafit-proxy**	**Adhesive patch**	**Al**	**Polyethylene**	**Adhesive plate**
E_1(Gpa)	50	208	155	2.29	72.4	0.55	1.1
E_2(Gpa)	15.20	25.44	12.10				
E_3(Gpa)	15.20	25.44	12.10				
G_{12}(Gpa)	4.70	7.24	4.40	0.842	28		0.382
G_{13}(Gpa)	4.70	7.24	4.40				
G_{23}(Gpa)	3.28	4.9	3.20				
V_{12}	0.254	0.1677	0.248				
V_{13}	0.254	0.1677	0.248				
V_{23}	0.428	0.36	0.458	0.36	0.33	0.3	0.44
ρ = Density (kg/m^3)	1900	2000	1600	874	2700	918	1200

3.2 Boundary Conditions of the Problem

The boundary conditions and loading scenarios for the analyzed parts in this study are as follows:

The parts are loaded solely in the X-direction. All degrees of freedom are constrained on one side of the part, effectively fixing that edge. On the opposite side, the part is only allowed to move in the direction of the applied load, i.e., the X-direction. This setup simulates a uniaxial loading condition.

The magnitude of the applied load is 100 (MPa). This load is introduced to the part in an increasing, linear fashion throughout one second. This gradual load application ensures a controlled and realistic loading scenario.

Figure 6 visually represents the boundary conditions and part loading implemented in the Abaqus software for this analysis. The fixed edge, the direction of the applied load, and the loading profile are all clearly depicted in the figure, allowing for a comprehensive understanding of the problem setup. The carefully defined boundary conditions and loading parameters are crucial for accurately simulating the behavior of the analyzed parts and obtaining reliable results from the finite element analysis.

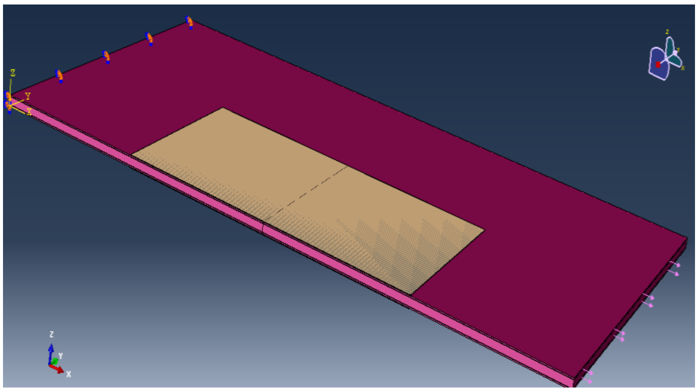

Figure 6. Boundary conditions of sample composite sheet

4. Results and Discussion

4.1 Investigating Symmetry in the Effect of One-Sided and Two-Sided Patch Repair

In the physical reality of one-sided patch repair, the change in the neutral axis of the structure causes the forces entering the repaired area to be off-center. This creates a significant torque in the connection, leading to the curvature and bending of the repaired structure. This bending can be observed in the patch application area, which is one of the key disadvantages of one-sided repair techniques (Figure 7). In contrast, two-sided patch repair techniques demonstrate a more symmetrical load transfer. When forces are applied, the symmetric nature of the two-sided patch prevents any deformation along the Z-axis (Figure 8). This symmetric load distribution is a significant advantage of the bilateral patch repair approach, as it helps maintain the repaired structure's original shape and integrity.

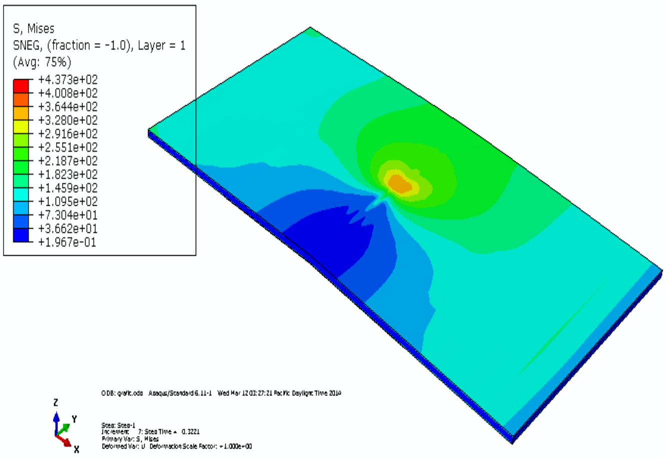

Figure 7. Boundary conditions of sample composite sheet

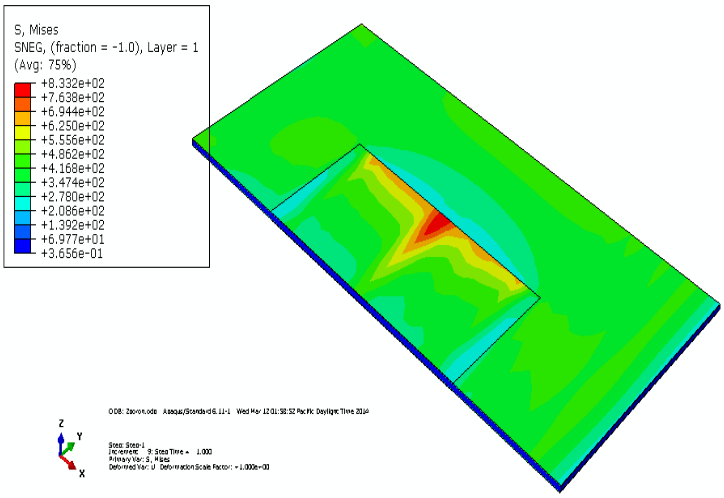

Figure 8. Bilateral restoration by Boron-epoxy patch

4.2 Comparison of Stress and Strain at the Crack Location

To evaluate the performance of the repair techniques, the study considered an applied tensile load of 100 (MPa) in the x-direction, applied throughout 1 second at equal intervals. This loading scenario allowed for the strain analysis developed at the crack tip in the tested samples, as shown in the strain-time diagram (Figure 9).

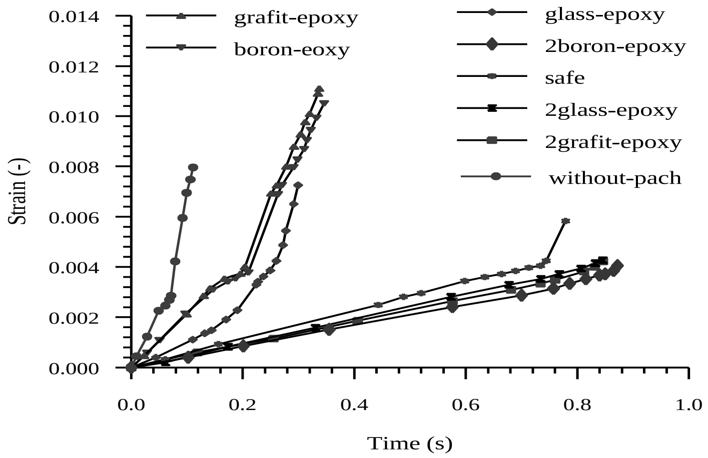

Figure 9. Strain vs. time diagram

The results reveal that the two-sided patch repair approach is more effective in reducing the stress (σ_x) over a longer duration than the one-sided repair. Specifically, using boron-epoxy composite patches on both sides of the cracked structure demonstrates the best performance in mitigating the strain development at the crack location. This superior strain reduction can be attributed to the symmetric load transfer and the uniform stress distribution achieved with the two-sided patch configuration. The bilateral repair's symmetry helps better manage the stress concentrations at the crack tip, leading to a more gradual and controlled strain development over time.

In contrast, the one-sided patch repair exhibits a less effective strain reduction, as the asymmetric load transfer and the resulting stress concentrations at the crack tip can lead to a more rapid and pronounced strain buildup. Therefore, the two-sided boron-epoxy patch repair emerges as the preferred approach for optimizing the structural integrity and durability of the repaired component by minimizing the detrimental effects of strain at the crack location. The symmetry in the load transfer and the absence of bending or deformations in the Z-axis are crucial factors when considering the long-term durability and performance of the repaired structure. By preserving the original shape and minimizing distortions, the two-sided patch repair approach can improve structural integrity and restore the component's functionality more reliably.

Due to the superior performance of the two-sided patch repair approach, as demonstrated by the reduced stress and strain at the crack location, the study further explored optimizing the composite patch design. To this end, the researchers employed two optimization techniques - the Genetic Algorithm (GA) and the Imperialist Competitive Algorithm (ICA) - to develop optimized composite patches for the bilateral repair configuration. The decision to focus on the bilateral patch repair was driven by the key advantages observed, such as the absence of bending deformation and the more effective mitigation of stress and strain at the crack. By applying the optimization algorithms to the two-sided patch design, the researchers aimed to enhance the repair solution's performance and efficacy.

After applying a tensile load of 100 MPa incrementally over 1 second to the test specimens, the stress developed at the crack tip was analyzed and presented in the stress-time diagram (Figure 10). The results demonstrate that using two-sided patches reduces the crack tip stress more effectively than the one-sided repair approach. Furthermore, applying the boron-epoxy composite patches on both sides of the cracked specimen provides the best stress mitigation performance among the tested samples.

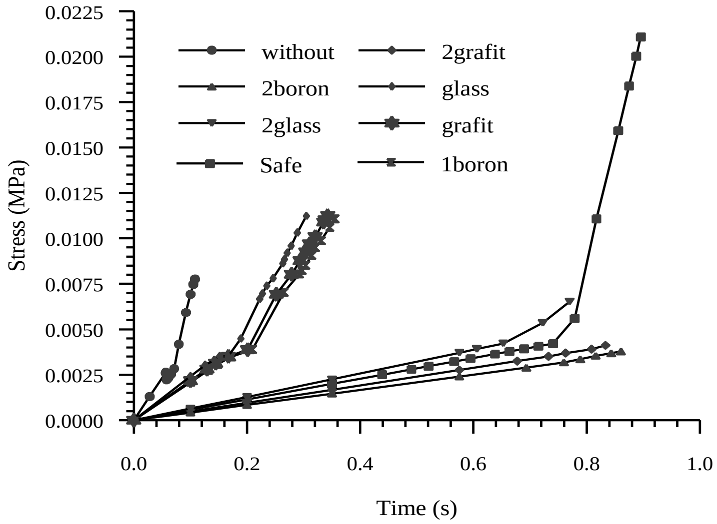

Figure 10. Stress versus time diagram

The superior stress reduction achieved with the bilateral boron-epoxy patch repair can be attributed to the symmetric load transfer and the uniform distribution of stresses across the crack location. The symmetric nature of the two-sided configuration helps to alleviate the stress concentrations that typically develop at the crack tip, leading to a more gradual and controlled stress buildup over time. In contrast, the one-sided patch repair exhibits a less effective stress reduction, as the asymmetric load transfer and the resulting stress concentrations at the crack tip can lead to a more rapid and pronounced stress development. Therefore, the two-sided boron-epoxy patch repair emerges as the preferred approach for optimizing the structural integrity and durability of the repaired component by minimizing the detrimental effects of stress at the crack location. The findings from this stress analysis further reinforce the advantages of bilateral patch repair, mainly when using the optimized boron-epoxy composite material. This approach demonstrates the potential to significantly improve the stress management and overall structural performance of the repaired components, making it a valuable solution for various engineering applications.

The analysis of stress and strain for the damaged sheet without a patch and the healthy sheet with one-sided and two-sided patches made of glass-epoxy, graphite-epoxy, and boron-epoxy materials is shown in Figure 11. The results indicate that the repair with double-sided patches can withstand higher stresses. Furthermore, the stress tolerance of the repair with double-sided patches is closer to the healthy state of the sheet, suggesting that this repair method is acceptable. The optimization of the composite patches reveals that the use of a boron-epoxy composite patch has the highest possible stress tolerance at equal strain levels. This is a significant finding, suggesting that the boron-epoxy composite material may be the most suitable choice for repairing the damaged sheet.

The diagram in Figure 11 illustrates the relationship between stress and strain for the various repair configurations. This visual representation helps to convey the relative performance of the different patch materials and configurations, allowing for a more comprehensive understanding of the repair process and its effectiveness. In summary, the analysis demonstrates that the repair with double-sided patches, particularly those made of boron-epoxy composite, can provide the most effective solution for the damaged sheet, as it exhibits the highest stress tolerance and closest performance to the healthy state of the sheet.

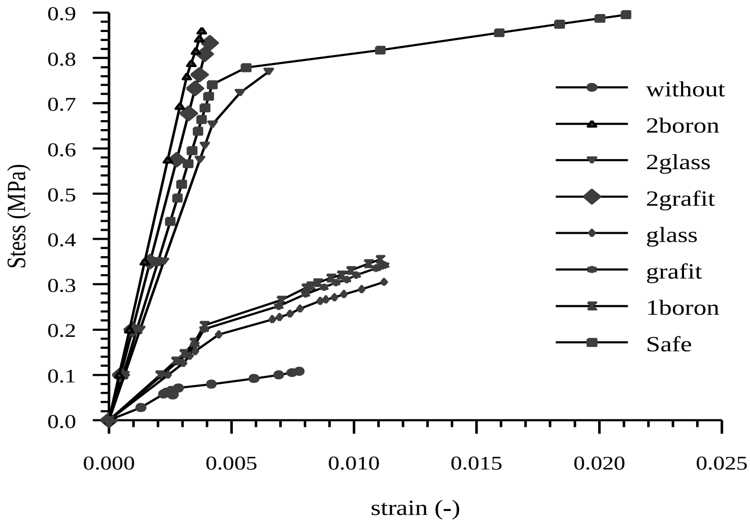

Figure 11. Stress versus strain diagram

4.3 Impact of Patch Layer Arrangement on Crack Opening Displacement

The arrangement of the patch layers significantly impacts the displacement of the crack opening points, as illustrated in Figure 12. This figure clearly shows the increase in the length of the crack in the direction of the crack created in the arrangement of different layers in the patches on the sample piece. Furthermore, Figure 13 depicts the stress created along the length of the crack. This visual representation provides valuable insights into the stress distribution within the damaged area. The analysis of these results indicates that double-sided patches are more effective in reducing the crack opening at higher stress levels. Specifically, using a boron-epoxy composite patch in a bilaterally symmetric arrangement is the best solution for reducing the crack opening and minimizing the stress at the crack tip.

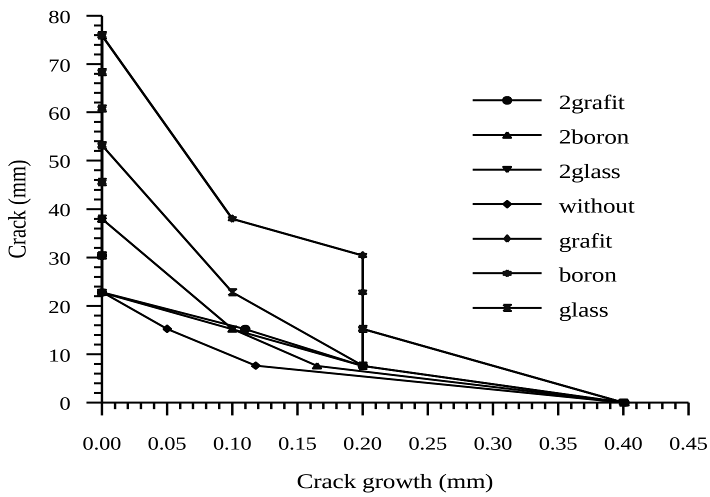

Figure 12: Variation of Crack Width with Crack Length

This finding is significant, as it suggests that the strategic placement and configuration of the patch layers can significantly enhance the overall effectiveness of the repair. By optimizing the patch arrangement, the crack opening can be effectively controlled, and the stress concentration at the crack tip can be reduced, leading to a more robust and reliable repair solution. The visual representations in Figures 12 and 13 provide a clear and comprehensive understanding of the crack behavior and stress distribution, enabling engineers and technicians to make informed decisions regarding the most suitable repair approach for the damaged structure.

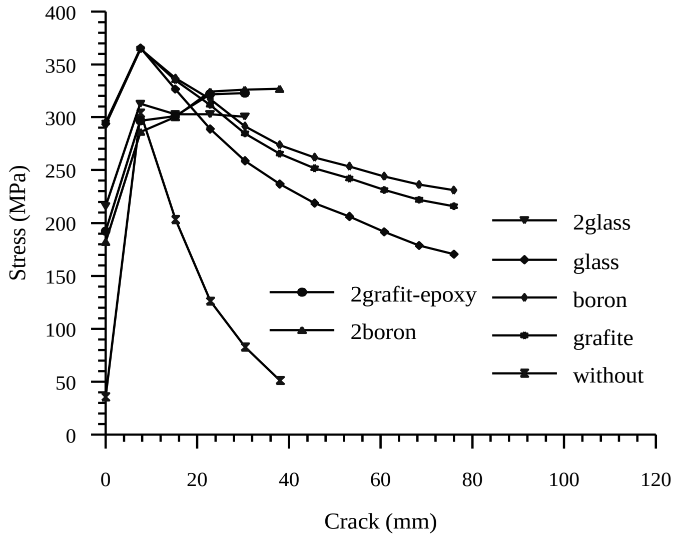

Figure 13: Stress Distribution along the Crack Length

4.4 Optimization of the Problem

Considering that an applied load of 100 MPa is applied to the sheet tensile in the x-direction throughout 1 second at equal intervals, the strain and the stress created at the crack tip in the tested samples are shown in Figures 14 and 15. The results indicate that the repair using bilateral patches will reduce the stress σ_x over a longer time. Using boron-epoxy composite patches on both sides of the crack has the best effect in reducing the strain.

Considering the better results obtained with bilateral patches and the absence of bending when using these composite patches, the study also employed optimized composite patches using Genetic Algorithm (GA) and Imperialist Competitive Algorithm (ICA) methods, which were applied bilaterally. These advanced optimization techniques allowed for further refinement and improvement of the patch design, leading to even more effective stress and strain reduction at the crack tip. By combining the benefits of bilateral patch application and the power of computational optimization methods, the overall performance of the crack repair solution was significantly enhanced.

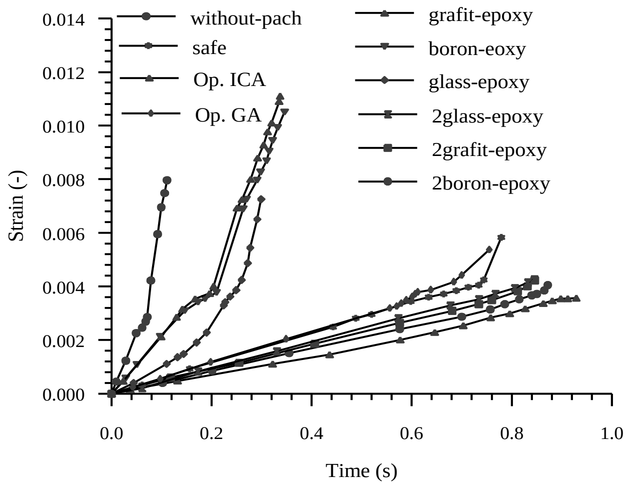

Figure 14. Strain-time diagram and its comparison with optimization in patches

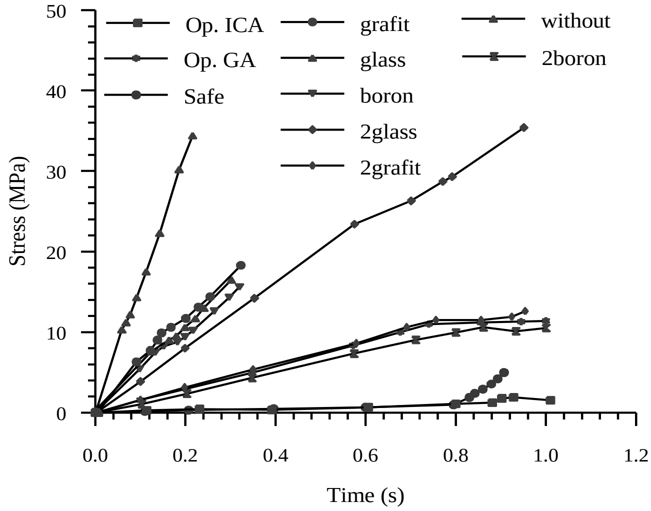

Figure 15. Stress-time diagram and its comparison with optimization in patches

The stress and strain analysis of the damaged sheet without a patch, the healthy sheet, and the repair states with one-sided and two-sided patches using different composite materials (glass-epoxy, graphite-epoxy, and boron-epoxy) are shown in Figure 16. The analysis also includes the optimized modes of the Genetic Algorithm (GA) and the Imperialist Competitive Algorithm (ICA). As can be seen from the figure, the repair with double-sided patches can withstand higher stresses compared to the other states. Furthermore, the stress tolerance of the repair with double-sided patches is very close to that of the healthy state of the sheet, indicating that this repair method is acceptable.

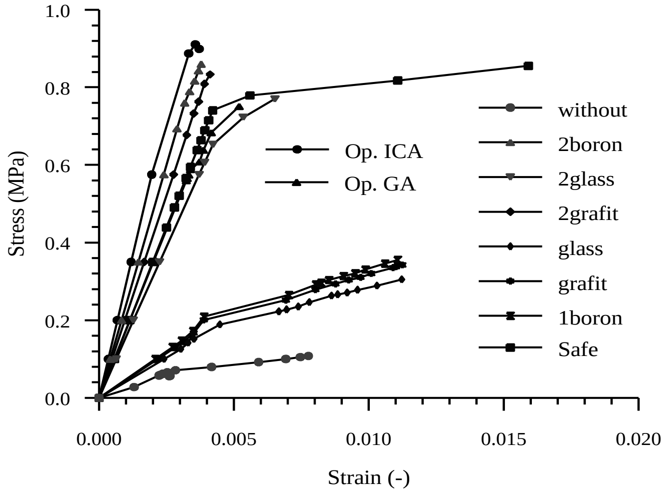

Figure 16. Diagram of stress and strain in different states

The analysis results of the optimized composite patches show that the patch optimized using the Imperialist Competitive Algorithm (ICA) method has the highest possible stress tolerance at equal strain levels. This suggests that the ICA-optimized patch is the most effective solution for repairing the damaged sheet, as it can restore the material's structural integrity to a level close to the healthy state. The use of advanced optimization techniques, such as GA and ICA, in designing the composite patches has enabled the identification of the most suitable repair solution. The ability to withstand higher stresses and the proximity of the repaired state to the healthy state make the two-sided patch with ICA optimization a promising approach for restoring the structural integrity of the damaged sheet.

The composite patches have been optimized using two different optimization methods: the Genetic Algorithm (GA) and the Imperialist Competitive Algorithm (ICA). The sample piece has been modeled and compared with the previous results using the data obtained from these algorithms. As shown in Figures 17 and 18, the composite patches can significantly reduce the crack growth and increase the rupture load when optimized using the Imperialist Competitive Algorithm (ICA) method. Specifically, the double-sided patches are more effective in reducing the crack opening at higher stress levels, and the patch optimized with the ICA method provides the best solution in this regard.

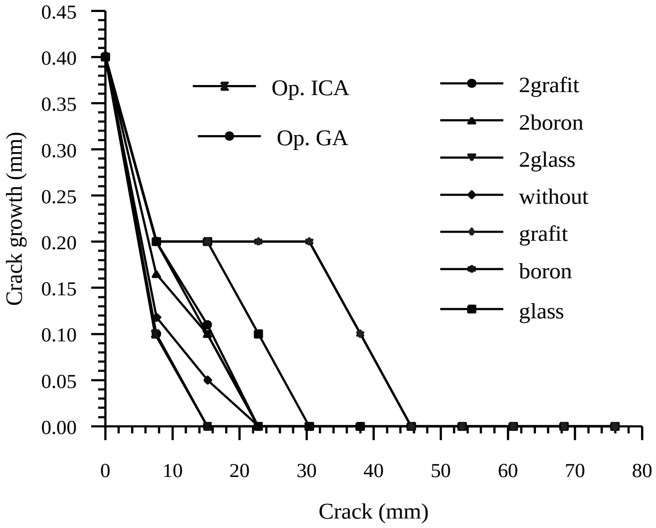

Figure 17. Crack width values along the increasing crack length

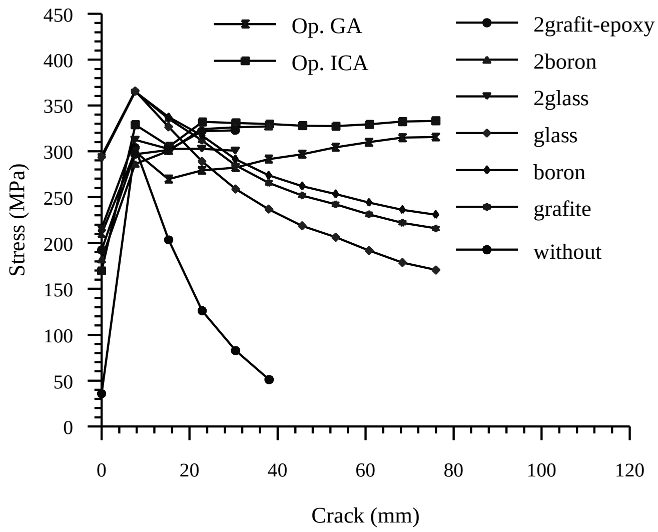

Figure 18. Stress along the length of the crack

The ability of the ICA-optimized patches to effectively control the crack growth and increase the rupture load can be attributed to the superior optimization capabilities of the ICA method. The ICA algorithm is known for its efficient exploration of the design space and its ability to converge to the global optimum, which, in this case, has led to the identification of the most effective patch design. In contrast, the patches optimized using the Genetic Algorithm (GA) method, while also showing improvements, do not perform as well as the ICA-optimized patches regarding crack reduction and load-bearing capacity. This highlights the importance of selecting the appropriate optimization technique for the specific problem, as the ICA has demonstrated its superiority over the GA in this particular application. The results presented in Figures 17 and 18 illustrate the effectiveness of the ICA-optimized composite patches in enhancing the structural integrity of the damaged component. This information can be valuable for engineers and researchers designing and optimizing composite repair solutions for various applications.

5. Conclusion

This study investigated the effectiveness of composite patches with different materials (glass-epoxy, graphite-epoxy, and boron-epoxy) in repairing a damaged sheet. The patches were applied on both sides and a single side of the damaged sheet. The patches had a rectangular shape and consisted of 4 layers. The analysis revealed that when using one-sided composite patches, a significant moment is created at the connection, leading to the part's curvature, which is a disadvantage of this repair approach. In contrast, using two-sided composite patches does not result in this undesirable curvature. Comparing the various performance metrics, such as strain-time, stress-time, stress-strain, stress-displacement, stress-distance, stress-crack length, and crack length-crack width, it can be concluded that the repair with two-sided patches is closer to the behavior of the intact sheet. Among the composite materials used for the 4-layer patches (glass-epoxy, graphite-epoxy, and boron-epoxy), the boron-epoxy patches exhibited the best structural strength and load-bearing capacity performance. The results suggest composite materials with a higher elastic modulus as the patch material can effectively reduce the stress intensity factor, stress, and strain at the crack tip. This finding is particularly relevant for designing and optimizing composite repair solutions, as it highlights the importance of selecting the appropriate patch material to achieve the desired structural integrity. The comprehensive analysis presented in this study provides valuable insights for engineers and researchers working on developing and implementing composite repair techniques. The comparative evaluation of different patch configurations and materials can guide the selection of the most suitable repair solution for a given application, considering factors such as structural performance, ease of application, and cost-effectiveness.

In optimizing the problem, three important factors were considered: load-bearing capacity, weight, and cost. The analysis revealed that the bilateral repair using the patch obtained from the Imperialist Competitive Algorithm (ICA) optimization method results in the least strain and the lowest stress at the crack tip. The analysis of various performance graphs, such as stress-strain, stress-displacement, and stress-crack length, showed that the ICA-optimized patch provides the best results among all the tested patches. Furthermore, the behavior of the ICA-optimized patch is the closest to the analysis of the healthy, undamaged sheet, indicating its superior performance in restoring the structural integrity of the damaged component. The results of the crack length growth in the repair using different patches were compared and validated using the Paris law equation. The findings demonstrate that using the composite patch optimized by the ICA method significantly reduces crack growth and increases the rupture load.

This optimization approach, which considers the critical factors of load-bearing capacity, weight, and cost, has identified the most effective repair solution. The ICA-optimized patch minimizes the strain and stress at the crack tip. It exhibits the closest performance to the healthy sheet, making it a highly desirable choice for repairing damaged structures. The ability of the ICA-optimized patch to outperform the other repair solutions, including those obtained from the Genetic Algorithm (GA) and other conventional methods, highlights the importance of employing advanced optimization techniques in designing composite repair solutions. The ICA's efficient explorations of the design space and its convergence to the global optimum have been instrumental in identifying the optimal patch configuration and material selection.

These findings can be valuable for engineers and researchers working on developing and implementing composite repair technologies, as they provide a comprehensive understanding of the factors contributing to the repair solution's effectiveness. The insights gained from this study can guide the selection and optimization of composite patches to ensure the restoration of structural integrity and the overall performance of the repaired component.

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