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Numerical Modeling of Stress Ratios in Single-Lap Adhesive Joints with Geometrical Modifications

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Abstract. This study aims to analyze the effect of variations in aluminum strip geometry and Araldite adhesive on the mechanical strength of single lap joints. A two-dimensional numerical model was developed in Abaqus/Standard using cohesive zone elements, the Benzeggagh-Kenane (B-K) model, and a quadratic stress criterion to validate the experimental results. The results show that the developed model is capable of accurately describing the stress distribution and the effect of secondary bending moments through the ratio of normal stress to shear stress. The application of chamfer geometry to the adhesive area proved to be effective in reducing secondary bending moments and increasing joint resistance. A comparison between the experimental and numerical simulation results showed a deviation of less than 15.5%, confirming the validity of this model. This study highlights the importance of geometric optimization in improving the mechanical strength and reliability of adhesive joints.

Keywords: Aluminum-epoxy composite, Benzeggagh–Kenane model, cohesive zone elements, stress ratio, numerical modeling.

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1. Introduction

Optimizing building structures requires minimizing the environmental footprint of materials and construction techniques while simultaneously cutting costs. A significant way to achieve this is by decreasing the structure's weight, which subsequently lowers the amount of fuel used and enhances how efficiently the structure handles loads. The use of adhesive joints, compared to mechanical joints, has been shown to reduce additional weight and provide more even stress distribution and better load capacity [1-9]. Single-layer adhesive joints are widely used due to their simple geometry and structural effectiveness, although load eccentricity can cause bending and high shear stress along the adhesive [10-12].

Bonding with adhesives, particularly in aluminum-epoxy joints, has been used in the manufacture of aircraft fuselages and main wings for more than six decades, although its use is still less common than mechanical joints [4-5]. Its advantages include not adding additional weight and avoiding stress concentrations due to holes in mechanical joints [6-9]. Several studies have analyzed single-lap configurations without geometric modifications [13-15], but these studies often fail to quantitatively explore the combined effects of geometric variations and failure mechanisms. This creates an important gap, as previous studies have not systematically evaluated the influence of geometric variations on stress distribution or stress ratio, which are key indicators of secondary bending and crucial for joint design optimization.

The complexity of adhesive joint performance is influenced by adhesive properties, surface preparation, and joint geometry, so predicting structural behavior requires careful numerical analysis. Improvements in computing power have encouraged the use of finite element simulation as an efficient and economical approach to evaluate the integrity of adhesive joints and factors such as overlap duration, adhesive damage, stress distribution, and failure mechanisms [16-19]. This approach allows for more accurate evaluation of failure risk and design optimization than purely experimental methods.

This study centers on building a finite element simulation to determine the impact of changing geometric features, such as "the edge treatment (beveling and chamfering) of the material and the curvature (rounding) of the adhesive, on the tensile strength of single-layer composite bonds. The main emphasis of the analysis is cohesive failure, and the relationship between the maximum shear stress and the maximum normal stress in the adhesive (the stress ratio) is used as a measure to understand the influence of secondary bending and how stresses are spread out". This approach facilitates a comprehensive evaluation of the combined effects of geometric variations, which have not been extensively studied in previous studies.

The novelty of this research lies in the integration of edge trimming and chamfering effects on materials and adhesives, as well as the use of stress ratio as the main evaluation metric. Its main contributions are providing more accurate design guidelines for aluminum–epoxy joints, improving joint resistance to load eccentricity, and expanding understanding of stress distribution mechanisms in single-layer joints. By understanding the effects of edge trimming and chamfering and using stress ratio as an indicator, researchers and designers can reduce load eccentricity that causes excessive bending and high stress on the adhesive. The study also broadens the comprehension of stress patterns and failure processes in single-layer joints, giving a more robust basis for optimizing how adhesive joints are used in structures.

2. Methods

The method used in this study is a combination of numerical and experimental approaches, where numerical modeling is performed using Abaqus/Standard with the Cohesive Zone Model (CZM) to simulate the behavior of Araldite 2015 adhesive on aluminum strips. Experimental testing was conducted on five joint configurations with measurements of tensile strength, stress distribution, and the ratio of normal stress to shear stress.

2.1 Research Design and Geometric Configuration

This study analyzes five geometric configurations of single joints, consisting of the reference single joint, surface pulling of the joint, angular cutting of the bonded material, angular cutting of the adhesive, and simultaneous angular cutting of the material and adhesive at the same angle ($\theta = 15°$).

The specimens are all 180 mm long (Lt) and feature a 50 mm overlap (Ls), a 3 mm substrate thickness (ts), and a 0.2 mm adhesive layer (tad). The surface reduction configuration uses a=2.5 mm and d=0.8 mm. The values for the overlap length and chamfer angle were selected based on earlier studies and literature reviews demonstrating their considerable impact on both stress patterns and overall joint strength.

2.2 Numerical Modeling

To model the behavior of Araldite 2015 adhesive on aluminum, numerical analyses were run in Abaqus/Standard with the CZM. The CZM blends concepts from Fracture Mechanics and Material Strength and uses a traction-separation law for tensile and shear stresses to simulate crack growth. The research's chief aim is to evaluate damage initiation through the quadratic nominal stress (QUADS) criterion, as shown in the following equation:

$$\left\{\frac{t_n}{t_n^0}\right\}^2 + \left\{\frac{t_s}{t_s^0}\right\}^2 = 1$$

The parameters used in the equation are defined as follows: t_n^0represents the ultimate normal stress of the adhesive, while t_s^0represents the ultimate shear stress of the adhesive.

The start of weakening in the mechanical properties occurs upon meeting the damage-initiation requirement, with the traction-separation relationship being described in:

$$\{t\} = [K]\{\varepsilon\}\ldots\ldots\ldots\ldots (1)$$

In the numerical model, {ε} is the relative displacement vector consisting of normal (δn) and shear (δs) components, while [K] is the stiffness matrix of cohesive material and t denotes the nominal stress. Once the stress reaches the critical threshold, the material stiffness decreases progressively through the scalar variable d ($0 \leq d \leq 1$), where d = 1 indicates complete failure. Failure occurs when the material stiffness k reaches zero, causing delamination to begin.

2.3 Data Analysis and Parameter Justification

Data analysis focused on the influence of geometric variations on joint behavior, specifically stress distribution along the adhesive, the shear-to-normal stress ratio as an indicator of secondary bending, and maximum joint strength. Geometric features like the lap length, chamfer angle, and adhesive thickness were chosen based on existing research that proves they significantly impact the joint's mechanical strength. The combination of numerical and experimental approaches allows for cross-validation, so that simulation results can be compared and calibrated with real data.

3. Results and Discussion

3.1 Validation of the numerical model

Validation of the numerical model involved a comparative study where the predicted results were matched against our experimental data. The failure load of the single-lap adhesive joints was the parameter included in this validation process. The studies were carried out utilizing a total of five specimens in accordance with the guidelines outlined in ASMT Standard number D1002-10 [21]. Figure 4 presents a comparative analysis of the experimental and numerical findings, specifically in relation to the failure load versus displacement. We observed a strong relationship between the experimental and numerical results in our calculations. The discrepancy in peak load between the average experimental and numerical values was 15.5%. Therefore, the reference model can be considered validated.

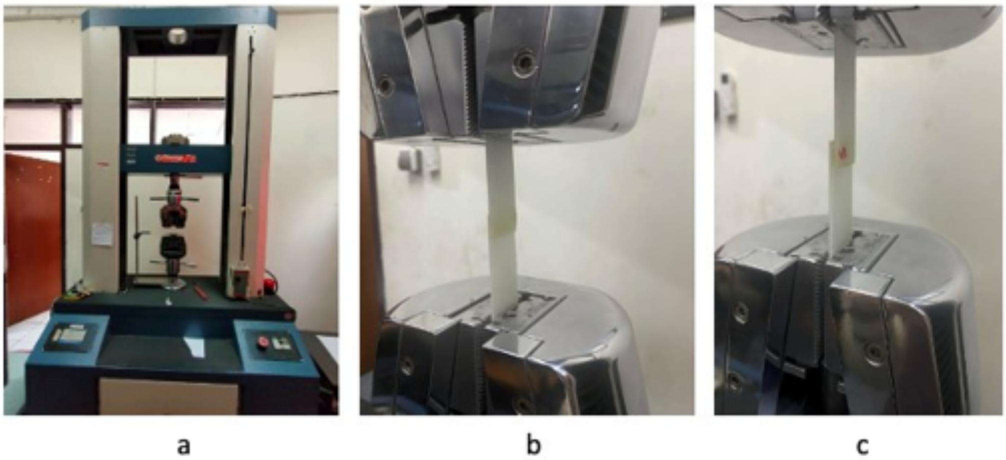

Figure 4. Experimental set-up and specimen before and before loading.

a. Microcomputer tensile test equipment plays a crucial role in collecting experimental data that verifies and aligns numerical models, such as cohesive zone elements, the B-K model, and quadratic stress criteria. This equipment allows testing of various geometric configurations of adhesive joints, measuring tensile strength, stress, and deformation to understand how changes in geometry affect the stress ratio and stress distribution in adhesive joints. The obtained data aids in the validation and calibration of numerical models, ensuring the accuracy and reliability of material behaviour predictions.
b. The specimen is mounted between two grips in the tensile testing machine. One grip usually remains stationary, while the other moves to apply the tensile force.
c. The tensile testing machine then applies a tensile force to the specimen by moving the moving clamp. This force is applied gradually and continues to increase until the specimen begins to deform or break. During the test, the machine records the tensile force applied and the elongation (stretching) of the specimen. This data is usually captured by a load cell (for force) and an extensometer (for elongation) attached to the machine. The tensile force and the change in length of the specimen are recorded in the form of a graph, typically a stress-strain curve.

After the reference model was validated, this study aimed to analyze the distribution profiles of shear stress, normal stress, as well as stress ratio. The results include the distribution of shear stress (Figure 5) and normal stress (Figure 6) in the adhesive for all geometric configurations.

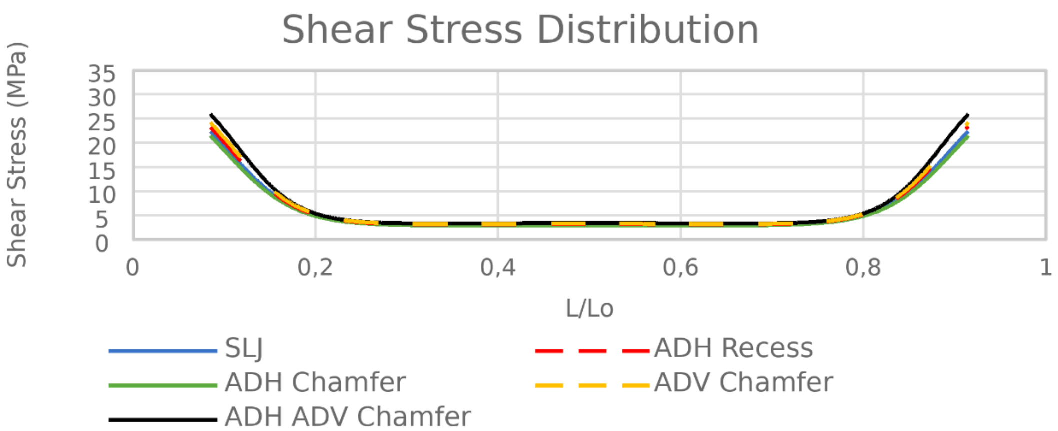

Figure 5. Shear stress distribution for all configurations

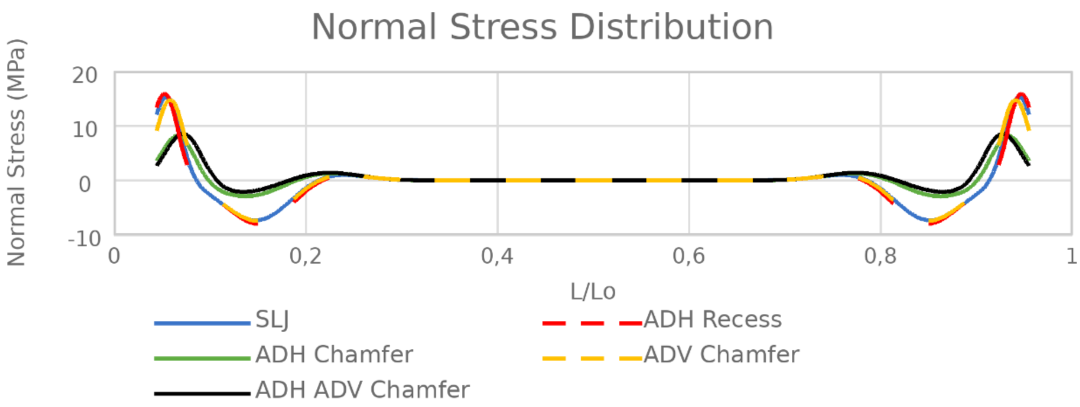

Figure 6. Normal stress distribution for all configurations

Figure 5 shows the shear stress distribution on the adhesive for all joint configurations. It can be seen that the highest shear stress values occur at both ends of the joint (around L/Lo = 0 and L/Lo = 1), while the middle section shows relatively low and stable stress. This phenomenon is caused by localized load concentration at the ends of the adhesive area. Configurations with chamfered edges on both the material and adhesive show a reduction in peak shear stress compared to standard joints (SLJ). This indicates that chamfered geometry can smooth the stress gradient in the transition area, thereby reducing the risk of adhesive failure initiation.

Figure 6 illustrates the normal stress distribution in all configurations, highlighting the difference in stress concentration near the joint tip. All configurations exhibit a rapid rise in normal stress at both ends of the joint (specifically at points 0 and 1 on the L/Lo axis). This intensification of stress at the joint's terminals stems from the limitations imposed by the geometry and the bending effects induced by the applied load.

In contrast, at the center of the joint, the normal stress is much lower because the load can be distributed more evenly, thus reducing the stress concentration and lowering the potential for failure in that area. As shown in the figure, the ratio of shear stress to normal stress (the stress ratio) is related to the greatest peel force. This correlation shows that higher stress ratios tend to trigger failures such as peeling or delamination, especially around the joint ends, where the stress concentration is highest.

The forthcoming figure will demonstrate the relationship between secondary bending and the resulting adhesive joint strength for this situation. Figure 6 illustrates the normal stress distribution across various joint configurations. From the figure, several key results can be identified:

The normal stress distribution shown in Figure 6 indicates that stress concentration varies significantly near the ends of the joints, with some configurations showing higher stress concentrations at the joint edges, which may lead to potential failure if not properly managed. The differences among configurations are also evident, as some joint designs produce a more uniform stress distribution, while others exhibit higher stress concentrations in specific areas. This shows that geometric configuration plays an important role in determining how stress is transmitted through the joint. High stress concentrations at the joint ends often indicate potential weaknesses that can reduce joint strength and durability under applied forces. Therefore, designs that minimize stress buildup at the edges may be more effective in achieving higher strength and longer service life. The data from Figure 6 provides valuable insight for joint design by helping designers select or optimize configurations that reduce stress concentration and enhance the overall strength of the joint.

Overall, Figure 6 helps identify joint configurations with better stress distribution and provides guidance for designing stronger and more efficient joints. Alongside the stress distribution findings, it is also possible to derive the correlation between the force and its displacement. Through this relationship, it becomes evident which geometric configuration exhibits the greatest maximum load. In general, there is a preference for high maximum loads due to the increased capacity of joints to endure bigger loads. The acquired data can be utilized to ascertain the appropriate geometric configuration for the SLJ joint structure.

Once the voltage distribution characteristics of the adhesive were understood, the analysis continued with modeling the force-displacement relationship to assess the cumulative effect of geometric changes on initial stiffness, maximum strength, and joint failure mechanisms, as shown in Figure 7.

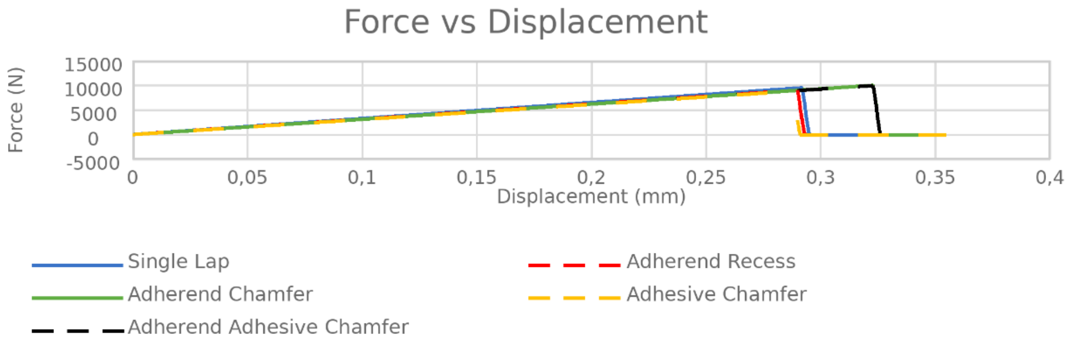

Figure 7. Force vs displacement for all configurations.

Figure 7 shows the relationship between force and displacement from simulation and experimental results for all configurations. All curves exhibit linear behavior in the initial stage, indicating an elastic phase in which stress increases proportionally to displacement. However, after reaching maximum force, the curves show a sharp decline due to adhesive debonding.

The ADH–ADV Chamfer configuration exhibits the maximum force and highest peak displacement, indicating an increase in the joint's resistance to tensile loads. In contrast, Adherend Recess shows the lowest release force, indicating that changes in geometry on the material side alone are not sufficient to optimize stress distribution. These results confirm that double chamfer modification (on the material and adhesive) is effective in reducing the secondary bending effect and improving stress distribution balance, resulting in a joint with better structural resistance. The findings indicate that a shear stress and normal stress ratio closer to equilibrium correlates with an enhanced total joint strength.

After analyzing the relationship between force and displacement as shown in Figure 7, the next step is to evaluate the correlation between the shear strength of the joint and the stress ratio, as shown in Figure 8.

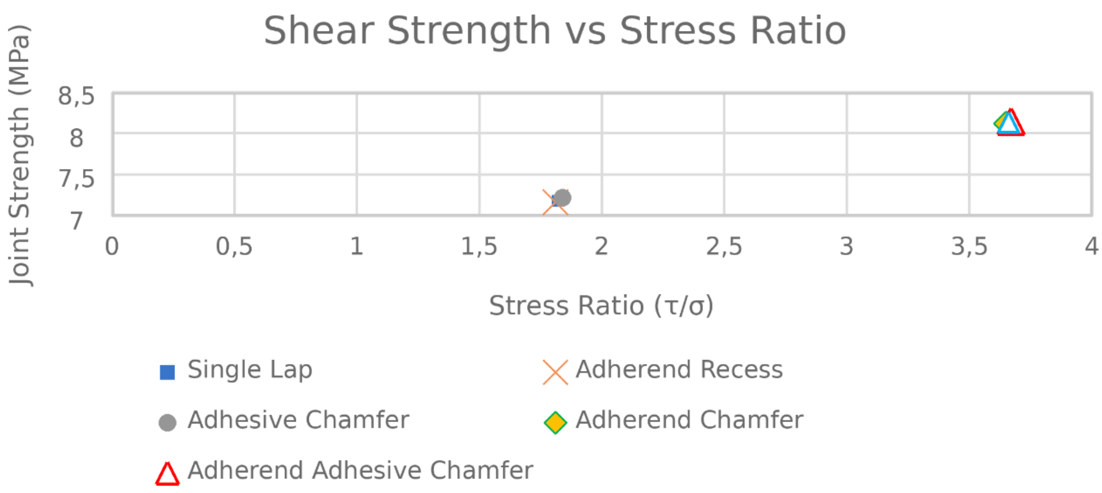

Figure 8. Shear strength vs stress ratio for all configurations.

Figure 8 shows that the chamfering geometry on the adhesive joint produces the highest maximum load compared to other configurations, while the single-layer joint without modification shows the lowest maximum load. When compared to the normal stress distribution results in Figure 6, it can be seen that the configuration with chamfering on the adhesive has lower normal stress at the end of the joint. This shows that geometric modification through chamfering can reduce stress concentration at the edge of the joint, which if left unchecked can exacerbate the effects of secondary bending.

By modifying the geometry, chamfering serves to distribute stress more evenly along the adhesive area, thereby reducing excessive local stress concentration, which is the main cause of premature shear failure. In addition, the reduction of the secondary bending effect also minimizes the appearance of additional normal stress at the adhesive end, which ultimately increases the overall strength of the joint.

These findings are consistent with previous research. Chen et al. [22] showed that optimizing the shape of the adhesive layer and the geometric configuration of the joint including the thickness of the adhesive and the shape of the adhesive layer significantly affects the shear strength of the joint. In their study, the use of a triangular or normal shape for the adhesive layer and a greater overlapping length were found to significantly increase shear strength. Conversely, standard adhesive joints without modification often experience high stress concentrations at the ends of the adhesive area, which can trigger premature failure [23].

Additionally, Pires et al. [24] found that a curved configuration in single lap joints (SLJs) did not significantly increase strength when used with ductile adhesives, but resulted in a 131% increase in strength with brittle adhesives due to their sensitivity to peak stress. This indicates that the concept of joint geometry modification whether through chamfering or curvature is effective in reducing stress concentration, and its effectiveness depends on the mechanical characteristics (ductility) of the adhesive used.

However, although the data shown in Figure 8 may appear to be close, the consistent trend shows that chamfering effectively reduces peak peel force compared to conditions without chamfering. This reduction is likely due to better stress distribution and lower stress concentration. Referring to relevant literature and considering factors such as chamfer geometry, adhesive properties and bonded materials, as well as load conditions, can provide further insight into the effectiveness of chamfering on adhesive joints [25], [26]. The use of statistical analysis can reinforce these observations.

4. Conclusion

This study developed a numerical model that accurately predicts stress distribution and failure mechanisms in single lap joints with various geometric configurations. The ratio of normal stress to effective shear stress indicates the influence of secondary bending moments, while the Benzeggagh–Kenane (B-K) failure criterion is reliable for mixed mode conditions. The application of chamfer geometry increases joint resistance by reducing secondary bending moments, and the validity of the model is confirmed by deviations of less than 15.5% compared to experiments. These findings emphasize the importance of geometry optimization and stress ratio analysis as guidelines for aluminum–epoxy joint design. The implications of this research include improved effectiveness and reliability in the design of adhesive joints, particularly aluminum–epoxy joints, in various structural applications, as the developed numerical model is capable of accurately predicting stress distribution and failure mechanisms. For further research, it is recommended to expand the study by exploring variations in adhesive materials and substrates, considering dynamic and cyclic load conditions, and testing more complex geometric configurations so that the model can be generalized and applied more broadly in practical structural design.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used Chat GPT in order to improve the language, grammar, readability, and academic writing style of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical approval

Not applicable

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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