

# Analysis of the Influence of Adhesive, Geometry, and Manufacturing Processes on Mixed Mode Stress Ratio in Single Lap Shear Adhesive Joint Structures of Aluminum and Composite Plates

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**Abstract:** In aircraft structures, composite plate joints often present significant challenges. Mechanical fastenings such as pins, bolts, or rivets require holes to be drilled in the plates, which reduces the strength of the laminate due to stress concentrations around the hole edges. These joints frequently become sources of structural failure in aircraft. Therefore, the design of composite plate joints is crucial to maintain structural integrity. Adhesive joints offer several advantages over mechanical joints, including the ability to join two different materials, more uniform stress distribution along the joint, and reduced weight since no bolts or rivets are needed. The most common adhesive joint design is the Single Lap Joint (SLJ), which is popular due to its simple geometry and high structural efficiency. However, the main drawback of the SLJ is load eccentricity, which leads to secondary bending and undesirable normal stresses along the adhesive edges. The hypothesis of this study is that SLJ conditions with optimal shear strength can be achieved through the right combination of adhesive type, bond surface preparation, and joint configuration. This study analyzes the influence of various adhesive materials, joint designs, and manufacturing methods using numerical modeling methods, validated with analytical approaches and ASTM standard testing. Numerical modeling is conducted using the finite element method with a cohesive zone model (CZM) approach to examine stress distribution in various cases, such as the impact of geometry, adhesive thickness, and joint length. The normal and shear stress distribution along the joint is found to significantly affect the strength of the SLJ, highlighting the importance of careful design and material selection in these applications.

**Keywords:** Cohesive zone model; Shear strength; Single lap joint; Stress ratio

## Introduction

The process of designing aircraft structures is a complex iterative process that involves the integration of design and manufacturing. The primary aspects to

consider are the reduction of structural weight to decrease fuel consumption, increase payload capacity, reduce operational costs, and minimize environmental impact (Gibson, 2007). Strategies to achieve structural weight reduction include the use of composite materials

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with low density and adhesives to join components (Shang et al., 2019).

Composite materials, as used in the structures of the Boeing B787 and Airbus A380, offer superior mechanical properties compared to conventional materials (Alam et al., 2022). The development of advanced composite materials has led to improvements in the stiffness and strength of these lightweight materials, changing the paradigm in aircraft shape design (Ozturk et al., 2024). However, achieving an ideal structure with minimal joints remains challenging due to limitations in disassembly and reassembly for inspection and maintenance, as well as the available material sizes for applications requiring minimal joints (Reis et al., 2020).

A critical part of the structure is the joint, which allows for the combination of sub-components into larger components. The use of adhesive bonding and mechanical fastening (rivets and bolts) has become the primary choice for joining composite structures (Galinska, 2020). In the context of adhesive bonding, the structure experiences internal and external loads that affect the stress distribution in the joint area. Analytical methods to predict the strength of adhesive structures have been developed for a long time, with testing standards such as ASTM D1002 for testing adhesive shear joints (Pramono & Junus, 2011).

This research aims to analyze the mixed mode stress ratio in Single lap shear adhesive joints using analytical, numerical, and experimental testing approaches. Through this approach, it is expected to develop a deeper understanding of the factors affecting the strength of adhesive joints in aluminum and composite plate structures (Da Silva et al., 2012). Additionally, this research will use classical lamina theory to understand the mechanical behavior of the composite materials used (Schwartz, 1986).

This research analyzes the influence of adhesive, geometry, and manufacturing processes on the mixed mode stress ratio in Single lap shear adhesive joints of aluminum and composite plate structures using analytical, numerical, and experimental approaches. The Single lap joint (SLJ) is a type of joint widely used in the manufacturing industry due to its simple geometry and high structural efficiency. However, this joint has a weakness in the form of load eccentricity, which causes secondary bending and undesired normal stress along the adhesive edge.

The adhesives used in this research include Epoxy adhesive and elastomeric adhesive. Epoxy adhesive is known to have higher adhesion strength compared to elastomeric adhesive (Hurme & Marquis, 2013). This is because Epoxy adhesive has better mechanical properties in terms of strength and stiffness, making it

more capable of withstanding shear loads applied to the joint.

Research also shows that the type of adhesive used significantly affects the joint strength. The use of Epoxy adhesive material results in higher adhesion strength values compared to elastomeric adhesive. Additionally, the proper use of adhesive can enhance the performance and reliability of joints in aluminum and composite plate structures.

The geometry of the joint also plays an important role in determining the joint strength. This research analyzes various adhesive thicknesses, namely 0.2 mm, 0.4 mm, 0.6 mm, and 0.8 mm (Chang et al., 2020). The research results indicate that the greater the adhesive thickness, the lower the joint strength. This is due to increased eccentricity resulting in greater secondary bending, hence the normal stress at the joint ends is also higher (Sánchez et al., 2018; Wei et al., 2020).

Additionally, the geometry of the adherend was also analyzed, including variations in thickness and length of the adherend. These variations affect the stress distribution and shear force on the joint. The research results show that the optimal geometry for a Single lap joint is one that has appropriate adhesive and adherend thicknesses to reduce stress and increase joint strength (Peres et al., 2022).

Different manufacturing processes were also tested to see their effects on joint strength. The methods used include clamping and sanding with grit 180 and 320. The research results show that sanding treatment with smaller (coarser) grit increases the adhesion strength value (Nazari et al., 2024). Additionally, the use of clamping also proves to increase the adhesion strength value, as it helps in optimizing the contact between the adhesive and the adherend during the curing process.

## Method

This research uses a multi-method approach which includes numerical, analytical and experimental testing. The following are the methodological steps used:

### *Numerical Model*

Creation of SLJ geometric models using finite element software (Goland & Reissner, 1944). Determination of material properties and boundary conditions for simulation (Da Silva et al., 2012). Creation of a mesh suitable for stress and strain analysis (Bracamonte et al., 2023).

### *Experimental Testing*

Making SLJ specimens with various types of adhesive and joint thickness (Abbasi et al., 2024). Tensile test using an MTS machine with a crosshead speed of 1 mm/minute (ASTM, 2010). Strain measurement with a

non-contact technique to ensure data accuracy (Nguyen & Trent, 2020).

*Data Analysis*

Comparison of experimental results with numerical and analytical results (Yang et al., 2019). Analysis of differences in joint performance based on adhesive type and joint thickness (Petrie, 2000).

**Result and Discussion**

*Comparison of Finite Element Model and Experimental Results*

The finite element model developed in this study shows good agreement with the experimental results. Here are some key findings.

*Influence of Substrate Material*

Composite substrates (Glass fabric – Epoxy resin) show different deformation behavior compared to aluminum clad 2024-T6 substrates (Kiss, 2023). Adhesive Araldite AW 106 and 3M 1300L show failure characteristics that are specific to the type of substrate used (Sánchez et al., 2018).

*Analysis of the Effect of Joint Thickness*

The thickness of the adhesive affects the stress distribution in the joint. Adhesives with a thickness of 0.2 mm show a more uniform stress distribution compared to those with a larger thickness (Carbas et al., 2021). Greater adhesive thickness tends to increase the ultimate load strength, but can also cause increased stress concentrations at the joint ends (Wang et al., 2022).

*SLJ Geometry Configuration Analysis*

Joint geometry influences stress distribution and failure patterns. Modifications to lap length and overlap angle can optimize joint strength (Shishesaz & Hosseini, 2020). This research successfully demonstrated that numerical and experimental methods can be used effectively to evaluate the performance of adhesive joints under mixed mode loading. The analysis results show that the substrate material, adhesive type, and joint thickness play an important role in determining the strength and reliability of the joint (Da Silva et al., 2012). These findings can be used as a basis for the development of stronger and more reliable adhesive joint designs in the future (Da Silva et al., 2012).

*Data Analysis and Interpretation of Results*

*Data Analysis*

In this study, data obtained from numerical, analytical and experimental tests were analyzed to evaluate the performance of adhesive joints. Following are some of the main steps in data analysis:

Stress and Strain Comparison: stress and strain data from numerical and experimental tests are compared to evaluate the suitability of the developed finite element model. The results show that the stress distribution in the numerical model is in good agreement with the experimental results under various load conditions (Da Silva et al., 2012).

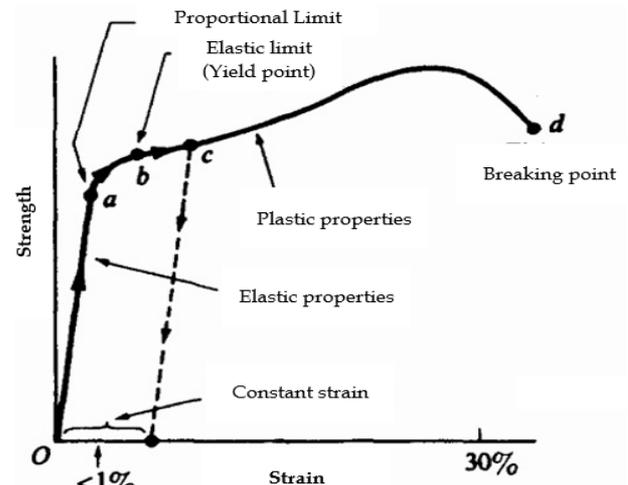


Figure 1. Stress-strain diagram

Effect of Adhesive Thickness: adhesive thickness significantly influences the stress distribution in the joint. Analysis shows that an adhesive thickness of 0.2 mm provides a more uniform stress distribution, whereas a larger thickness tends to increase the stress concentration at the joint ends (Wang et al., 2020).

Ultimate Load Strength Evaluation: The ultimate load strength of the adhesive joint is tested with various adhesive thicknesses and substrate types. The results show that greater adhesive thickness tends to increase the ultimate load strength, but can also cause an increase in stress concentration (Wang et al., 2022).

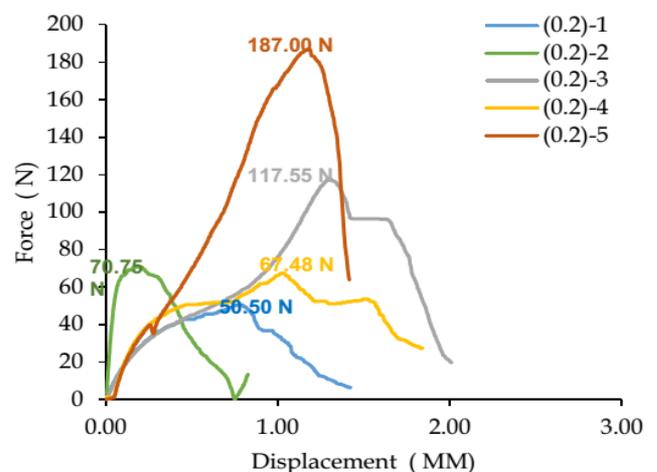
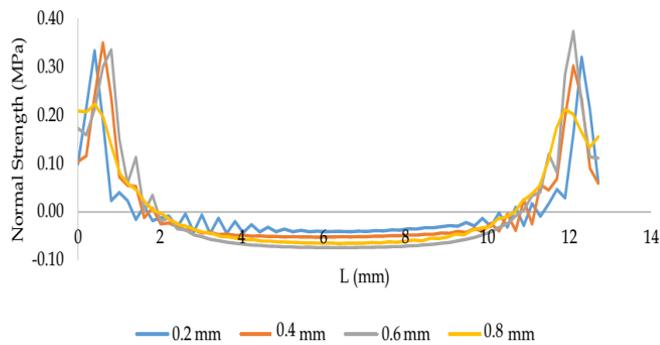


Figure 2. Single-lap Load vs Extension Curve, Adhesion Shear adhesive Thickness 0.2 mm



**Figure 3.** Normal stress distribution for all joint thickness configurations

**Effect of Joint Geometry:** variations in joint geometry, such as lap length and overlap angle, influence stress distribution and failure patterns. This modification can be used to optimize joint strength (Kafkalidis & Thouless, 2002).

#### Interpretation of Results

**Suitability of the Numerical Model:** The analysis results show that the developed finite element model has good agreement with the experimental data. This shows that this model is reliable for predicting stress and strain behavior in adhesive joints under combined mode I and mode II loading (Gonçalves & De Almeida, 2002).

**Effect of Substrate Material:** The substrate material has a significant influence on the deformation and failure behavior of the joint. Composite substrates such as Glass fabric - Epoxy resin show different behavior compared to metal substrates such as aluminum clad 2024-T6, indicating the need for appropriate material selection for a particular application (Gonçalves & De Almeida, 2002).

**Optimization of Adhesive Thickness:** Adhesive thickness is an important parameter that influences the stress distribution and ultimate load strength of the joint. An adhesive with an optimal thickness (e.g. 0.2 mm) can provide a more uniform stress distribution and increase the overall strength of the joint (Ramalho et al., 2020).

**Joint Geometry Design:** Joint geometry, including lap length and overlap angle, influences stress distribution and joint failure. Modifications in geometric design can be used to optimize the strength and reliability of adhesive joints, which is very important in engineering applications (Malekinejad et al., 2023).

From the data analysis and interpretation of the results, it can be concluded that the numerical and experimental methods used in this study provide consistent and reliable results for evaluating the performance of adhesive joints under mixed mode loading. Substrate material, adhesive thickness, and joint geometric design are key factors that influence joint strength and reliability. These findings can be used as a

basis for the development of stronger and more reliable adhesive joint designs in the future (Da Silva et al., 2012; Hirulkar et al., 2018; Wei et al., 2024).

## Conclusion

This research succeeded in developing and validating a finite element model to predict the mechanical behavior of adhesive joints in composite materials and aluminum. This research shows the significant impact of material type, adhesive type, and thickness on joint performance, providing valuable insights for optimizing adhesive joint design. The conclusions drawn from this research offer practical guidance and future research directions to improve the strength, reliability, and applicability of adhesive joints in structural applications.

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#### Author Contributions

The authors listed in this article contributed to the development of the article, and have read, approved the published manuscript.

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#### Conflict of interest

The authors declare no conflict of interest.

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