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Advances in Adhesive Bonded Joints for Composite Materials: A Comprehensive Review

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Abstract

Adhesive bonded joints have become increasingly significant across various high-tech industries, including aerospace, automotive, marine, and construction. This growing importance is largely due to their efficiency in joining lightweight composite materials, which are integral to modern engineering applications. In this review paper, we offer a comprehensive update on the latest advancements in adhesive bonded joints specifically for composite materials. The paper delves into several critical aspects of adhesive bonding, beginning with surface preparation. Proper surface preparation is crucial for achieving optimal bond strength and durability, and this paper explores the latest techniques and best practices in this area. It also examines current testing methods used to evaluate the performance of adhesive joints, ensuring that they meet stringent industry standards. Durability is another key focus of the review. We discuss various considerations related to the long-term performance of adhesive bonded joints, including environmental factors, load-bearing capacity, and resistance to aging and degradation. The paper also highlights recent innovations in adhesive technologies. These advancements include new formulations and types of adhesives that enhance bonding capabilities and overall joint performance. Additionally, we cover the latest developments in surface treatments, which play a critical role in improving adhesion by modifying the surface properties of composite materials. In summary, this review offers a thorough and up-to-date examination of adhesive bonded joints for composite materials, highlighting both recent advancements and ongoing challenges, while providing valuable insights into future research directions.

Keywords: *Adhesives, Composites, Failure Load, Joint Strength, Single Lap Joints*

1.0 Introduction

Fiber-reinforced composites have emerged as a compelling alternative to traditional metals in the construction of complex structural components. The adoption of these advanced materials offers several significant benefits, including a reduction in the number of components required, a decrease in overall weight, lower costs, and enhanced reliability. Unlike conventional metals, which are commonly joined using techniques such as riveting, bolting, gluing, and soldering, polymer matrix composites necessitate different joining methods. In this context, adhesive bonding, along with bolts and rivets, is commonly used. Notably, adhesive bonding is often preferred over traditional methods for its distinct advantages. Unlike conventional methods that require drilling holes for bolts and nuts, adhesive bonding eliminates this need, simplifying the joining process. Several reasons underscore the preference for adhesive

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bonding over conventional methods when joining both composite and metallic parts, as outlined by.

1.1 Design Simplification

Adhesive bonding allows for the minimization of parts, leading to a more streamlined and efficient design. This reduction in the number of components contributes to lower production complexity and cost.

- Elimination of Machining Operations: Adhesive bonding obviates the need for machining operations such as riveting, milling, and forming. This not only reduces manufacturing time but also lowers associated costs.
- Enhanced Visual Appearance: The absence of visible fasteners or mechanical joints improves the aesthetic appeal of the final product, providing a cleaner and more polished appearance.
- Superior Shear Strength: Adhesive bonding can provide up to three times the shear force compared to traditional rivets and spot weld joints, offering stronger and more reliable connections.
- Efficient Large-Area Bonding: The technique allows for bonding large surface areas with minimal workforce and without requiring specialized skills, making it more accessible for various applications.
- Excellent Thermal and Electrical Insulation: Adhesives offer outstanding thermal and electrical insulation properties, which can be crucial in applications requiring temperature control and electrical safety.
- Enhanced Damping Characteristics: The damping properties of adhesive-bonded joints surpass those of riveted joints, leading to better vibration and noise reduction.
- Flexibility in Material Combinations: Adhesives provide the flexibility to join diverse materials and metals, accommodating a wide range of combinations that might be challenging with traditional joining methods.

In summary, the advantages of adhesive bonding ranging from design simplification and cost reduction to enhanced performance characteristics make it a preferred method for joining both composite and metallic parts in modern engineering applications.

2.0 Joint Types

Adhesive bonding has emerged as the most desirable method for joining composite structural parts, given its numerous advantages. It excels in terms of strength-to-weight ratio, cost efficiency, and reduced need for extensive machining. However, despite these benefits, the design, analysis, and optimization of adhesive joints for maximum strength present considerable challenges. The use of lightweight composite structures has surged across various industries, including aerospace, automotive, construction, sports, electronics, and packaging. This rapid expansion has led to a significant increase in the application of adhesives for joining composite materials. Adhesives, typically non-metallic like the composites themselves, accommodate components of various sizes, shapes, and structures, further enhancing their versatility. The advantages of adhesive bonding over traditional joining methods are well recognized within the industry.

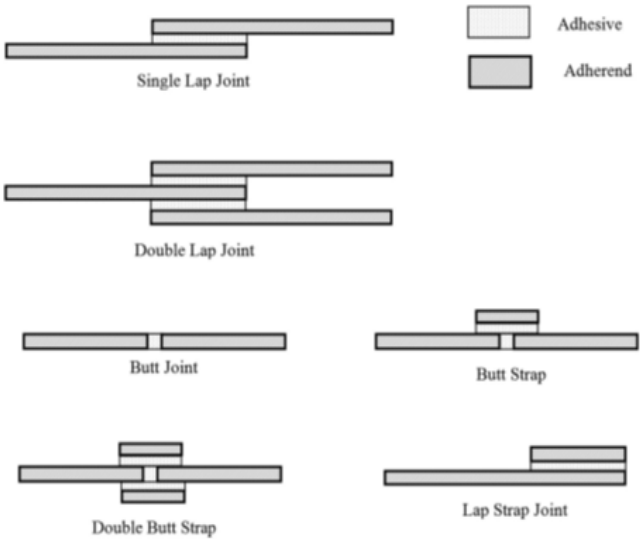


Figure 1. Different configuration of adhesive joints[3].



Figure 2. Typical T joints[1].



Figure 3. Typical L joints.

Adhesive joining methods offer superior load-bearing capacity, reduce stress concentrations, and provide greater design flexibility. Additionally, they exhibit excellent resistance to corrosion. One of the key benefits is the overall weight savings achieved, which is critical for applications where minimizing weight is essential. Furthermore, adhesives improve the aesthetic appearance of joints, particularly when joining dissimilar materials, contributing to a cleaner and more streamlined look. Given these advantages, high-performance adhesives are becoming increasingly prevalent in critical sectors such as construction, aerospace, and medical fields. Their ability to deliver robust performance while enhancing design flexibility and durability makes them a valuable choice for modern engineering applications.

Joint configuration is one of the key aspect in composite joint design. Different joint configurations are available for designers as described[1-4] (Figure 1). SLJ, DLJ, but joint and scarf joint are most commonly used joint configuration that have been analysed in the literature. Other type of joints such as T-joint, L-joint, tubular joint and corner joints were also analysed[5].

3.0 SLJs (Single Lap Bonded Joint)

Single Lap Joints (SLJs) are among the most commonly used types of joints in various engineering applications due to their simplicity and ease of construction[6,7]. Despite their widespread use, accurately determining the state of stress within SLJs presents significant challenges. One of the primary reasons for the popularity of SLJs is their straightforward geometry, which facilitates the evaluation of stress distributions within the adhesive layers. In a single lap joint, two structural materials referred to as adherends are joined together, typically using adhesives, glue, bolts, or a combination of these methods. The design of an SLJ involves overlapping the ends of the two adherends, creating a bonded region where no material is removed from the bond area. This simple overlapping arrangement makes SLJs relatively easy to fabricate and implement. Figure 4 illustrates the antisymmetric joining of the two adherends, highlighting the overlapping bond area where the adhesive is applied. The visual representation underscores the basic design of an SLJ, where the overlapping sections of the adherends are bonded together without the need for any material removal at the junction.

Despite their ease of construction, the stress analysis in SLJs can be complex due to factors such as the distribution of stresses across the adhesive layer and the potential for stress concentrations[6-8]. Accurate stress assessment is crucial for ensuring the reliability and performance of the joint, especially under varying load conditions. The simplicity of the SLJ geometry, however, remains a significant advantage in the initial stages of

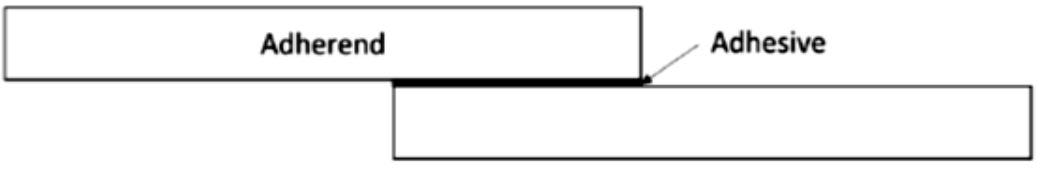


Figure 4. Single-lap joint.

design and evaluation, making it a popular choice in many engineering applications.

4.0 Joint Geometries

A thorough literature analysis focused on specific geometry and material behaviour has been systematically published, which helps to find the distribution of stress in any joint depends upon the normal structure and properties of both adhesives and adherends. Thickness of adhesive, surface hardness, overlap length and adhesion strength are major factors influencing the stress area of adhesive and adherence layers[9].

These joints are cheapest easiest type of bonded joints based on manufacturing conditions. However, the offset in the adherends causes bending couple in the joint, which creates higher stress at both ends of the overlap area resulted in improper distribution in load[8]. Adherend tapering has noticeable effect in reducing the peel stress. By using external taper with 300 fillet results in significant decrease in values of peel stress at the overlap ends[9,10]. Hildebrand *et al.* showed that modification of adherend ends by tapering, fillet, rounding and recessing for different combination of metal to FRP adherend and also adherend to adhesive bonding the joint strength can be increased by 90-150%, if the design is carefully estimated. The joint behaviour subjected to loading condition, geometry and different material in different industries were discussed in detail[11].

5.0 Effect of Bonding Dimensions

The performance and effectiveness of the adhesively bonded joints are affected by overlap length, bond thickness, and adherend width. The influence of each of the parameter is discussed in following sections.

5.1 Overlap Length

The overlap length in Single Lap Joints (SLJs) significantly impacts the joint's load-bearing capacity and overall strength. As the lap length increases, the joint's ability to sustain higher loads generally improves. However, the rate at which strength increases with overlap length is influenced by several factors, including the type and properties of the adhesive used, the composition of the adherends, and the specific loading conditions applied. Neto *et al.*[12] observed that ductile adhesives enhance the load-bearing capacity of SLJs in proportion to the increase in lap length. This is because ductile adhesives can better accommodate the stresses over a longer bonded area, improving overall joint performance. On the other hand, the failure mode of adhesive-bonded joints is influenced by the adhesive type, lap length, applied loading type, and adhesive thickness.

Typically, cohesive failure—where the adhesive fails internally—occurs when the overlap length is between 10 to 20 mm. In contrast, interlaminar failure, which involves the separation of layers within the composite material, is more common when the lap length is significantly longer.

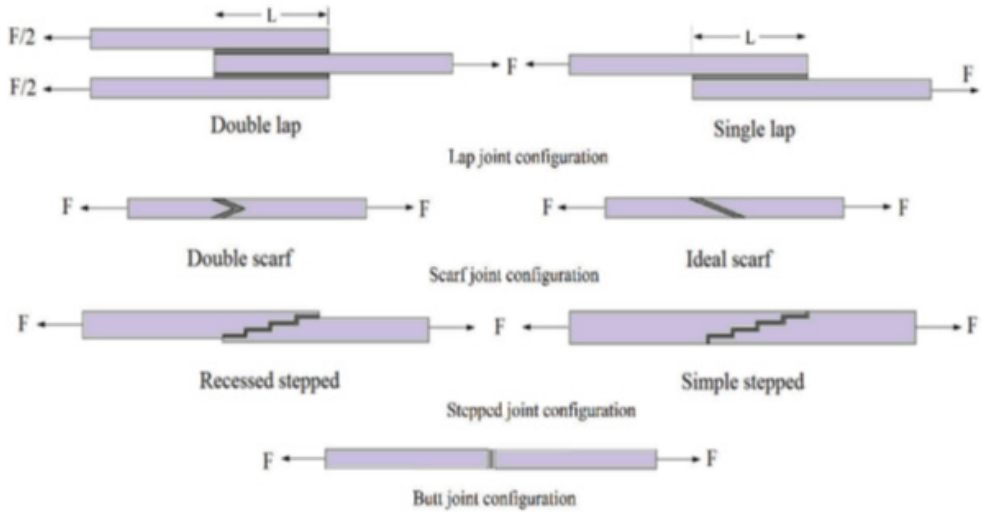


Figure 5. Single-lap joint[1].

This shift in failure mode is critical for understanding the performance of SLJs under different conditions. Pereira *et al.*,[13] investigated the performance of SLJs with overlap lengths of 30 mm and 60 mm under both static and fatigue loads. They found that joints with a 30 mm overlap performed better, suggesting that beyond a certain point, increasing overlap length does not necessarily result in proportional improvements in joint strength.

Ferreira JA and De Goeij[14,15] reported that for adhesively bonded composite joints, there is an optimal overlap length. Beyond this optimal length, joint strength does not increase significantly unless the properties of the adherends are enhanced, which often leads to interlaminar failure in composite laminates. This finding is consistent with observations by Neto and others.

Neto J. A.[16] also explored the impact of overlap length in metallic adherends, analyzing the load capacity and failure modes of carbon epoxy composite joints. Their research revealed that joints bonded with brittle epoxy adhesives tended to fail through delamination of the substrates. In contrast, joints with ductile adhesives displayed cohesive failures, with a linear increase in failure length corresponding to the increase in overlap length. This indicates that while ductile adhesives improve joint performance with increased overlap, brittle adhesives are more prone to structural failures.

In summary, while increasing overlap length generally enhances the load-bearing capacity of SLJs, the type of adhesive, failure modes, and optimal overlap length are critical factors that influence joint performance. Understanding these aspects is essential for designing effective and reliable adhesive-bonded joints.

5.2 Adhesive Thickness

Many analysis showed that joints with a 0.5 mm thickness exhibited maximum shear strength. It's important to note that the optimal adhesive thickness values are dependent on the type of adherends being joined. When transitioning to GFRP composites, the optimal adhesive thickness also changes accordingly.

5.2.1 Effect of Adherend Thickness

Under tensile loading conditions, the performance of adhesive-bonded joints is influenced by factors such as eccentric loading and bending moments. The strength of these joints can be evaluated based on these variables. Pereira's[13] research indicates that increasing the adhesive thickness from 1 mm to 1.5 mm can raise the failure load by approximately 18 percent. This increase in thickness not only enhances the yielding load but also positively impacts the bending moment capacity of the joint. However, the effectiveness of this increase is tempered by the joint's turning angle, which can decrease shear strength as the angle increases.

Grant L. D. *et al.*[17] demonstrated that the strength of an adhesive bond is directly related to the thickness of the adherends. Their findings confirm that thicker adherends generally contribute to greater bond strength.

Da Silva L. F. *et al.*,[18] examined the strength characteristics of discontinuous fiber composite substrates and identified a critical adherend thickness beyond which the interlaminar strength is surpassed. This suggests that there is an optimal thickness for the adherends, and exceeding this optimal value does not necessarily lead to improved joint strength. Instead, it emphasizes that joint performance is highly dependent on finding this optimal thickness.

Davies P. *et al.*,[19] conducted a study focusing on different adherend thicknesses and their impact on joint performance. Their experimental analysis included three different adherend thicknesses—2 mm, 3 mm, and 6 mm—to assess the robustness of Discontinuous Carbon Fiber Polymer (DCFP) Single Lap Joints (SLJs). The results revealed that while the shear strength difference between the 2 mm and 3 mm thicknesses was minimal, increasing the adherend thickness to 6 mm resulted in a significant reduction of more than 15 percent in shear strength.

In summary, the strength of adhesive-bonded joints is influenced by the thickness of the adherends, with an optimal value that maximizes performance. Both excessive and insufficient thicknesses can negatively affect joint strength, highlighting the importance of precise thickness optimization in achieving robust adhesive joints.

5.3 Bond Width

De Goeij *et al.*,[15] found that as the width of a bonded joint increases, the significance of strain or stress peaks diminishes. This means that, to maintain a constant energy release rate, it is crucial to ensure that the joint has a minimum width, irrespective of its overall size. While maintaining this minimum width is typically not an

issue in industrial applications, it is essential for precise characterization of the joint's performance. In practical terms, increasing the width of the bonding area from a rectangular to a square configuration can enhance the load-bearing capacity of the joint. Numerical analyses corroborate this finding, as they align closely with experimental data. This suggests that a larger bonding area can distribute stresses more evenly, improving the joint's overall strength.

Işcan and Hamit Adin[20] reported similar findings, noting that increasing the width of the adherends leads to greater load-carrying capacity and overall strength. Their experiments demonstrated that a specimen with a 10 mm width exhibited the lowest failure load. In contrast, specimens with a 30 mm width showed improved performance, indicating that increasing the joint width enhances the specimen's load-bearing capacity.

In summary, maintaining an appropriate minimum width for bonded joints is vital for consistent performance and energy release rates. The transition from rectangular to square bonding areas and an increase in adherend width are both effective strategies for improving joint strength and load-carrying capacity.

6.0 Surface Preparation

Surface preparation of adherends is a critical factor in enhancing adhesion and minimizing the impact of environmental degradation on bonded joints. The quality and reliability of an adhesive bond are significantly influenced by the preparation of the interface between the adhesive and the adherend surface. Research consistently shows that failures in bonded joints are often linked to poor surface preparation and inadequate processing conditions. Hart-Smith[21] has highlighted the importance of effective surface preparation techniques, particularly in applications such as aerospace manufacturing where bonding strength is crucial. For composite adherends, Hart-Smith[21] reported that traditional methods, such as peel ply, which were initially used to create a rough surface for better bonding, often lead to premature joint failure. This is because the peel ply technique, designed to create a textured surface, actually results in microscopically smooth furrows, which do not enhance bonding as intended.

Furthermore, the choice of cleaning agents plays a crucial role in surface preparation. Işcan B.[20] Emphasized that using detergent as a surface cleaner could leave behind additional contaminants on the bonding area, which can adversely affect bond quality. It is recommended to use a lint-free cloth instead of cotton to avoid leaving residues that could compromise the bond. Hart-Smith[21] compared the effectiveness of surface preparation using both mechanical abrasion and chemical modification methods versus simple cleaning processes. The results indicated that surfaces prepared through mechanical abrasion and chemical treatments exhibited superior performance compared to those prepared using only a simple cleaning procedure. This comparison underscores the importance of employing comprehensive surface preparation techniques to ensure strong and reliable adhesive bonds.

In summary, meticulous surface preparation is essential for achieving high-quality adhesive bonds and preventing joint failures. Effective techniques involve more than just cleaning; they include mechanical and chemical modifications that enhance the bonding interface and ensure long-term reliability.

7.0 Conclusion

Adhesive bonded joints continue to evolve as a crucial technology for joining composite materials, enabling lightweight structures with improved performance. This review highlights recent advancements in surface preparation, adhesive selection, joint design, testing methods, durability assessment, and the bonding of dissimilar materials. As technology advances, adhesive bonding is poised to play an increasingly pivotal role in the realization of innovative composite-based designs. The literature review confirmed that, the study of control variables such as geometric and material parameters, surface treatment, joint configuration etc. are important as they affect the performances in bonded joints. The literature review also confirms that factors various above mentioned are directly or indirectly influence the performance of joints.

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