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Adhesion mechanisms and mechanical performance of single-lap joints in FDM-3D printed: A review

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Abstract: Additive Manufacturing (AM), particularly Fused Deposition Modelling (FDM), has evolved from a rapid prototyping technology into a manufacturing approach for producing functional components across a wide range of industrial sectors. Nevertheless, the limited build volume of FDM systems has encouraged the use of adhesive bonding as a practical method for joining sub-components, with the single-lap joint (SLJ) configuration being among the most widely adopted designs. This review aims to provide an integrated analysis of the relationship between FDM-induced surface morphology, the adhesion mechanisms developed at the bonded interface, and their implications for stress distribution, shear strength, and joint failure modes. The findings indicate that the surface characteristics generated by the FDM process, including layer lines, stair-stepping effects, voids, and porosity, create interfacial conditions that differ fundamentally from those of homogeneous materials. These characteristics also produce a non-linear relationship between surface roughness and joint strength. Process parameters such as printing orientation and layer height were identified as key controlling factors that influence surface topography and adhesive performance. From a mechanical perspective, the eccentric load path inherent in SLJ configurations generates significant shear and peel stress concentrations at the overlap ends. These stress concentrations coincide with structurally weak regions that are intrinsically associated with FDM adherends, making them the primary sites for crack initiation and joint failure. Furthermore, modifications to overlap geometry and tailored adhesive distribution have been recognized as effective strategies for improving stress redistribution and enhancing the load-bearing capacity of the joint. This review highlights that the assessment of adhesive joints in FDM-manufactured components requires an integrated analytical framework that accounts for the coupled interactions among printing process parameters, surface conditions, adhesive properties, and progressive failure modelling. Such an approach is essential for the development of reliable structural joint designs for FDM-based applications.

Keywords: adhesive bonding; additive manufacturing; fused deposition modelling; interlayer bonding

1. Introduction

Additive Manufacturing (AM) has developed rapidly as an alternative to the limitations of conventional manufacturing methods. By selectively depositing material layer by layer, this technology provides high design flexibility and improved material efficiency compared with subtractive manufacturing processes (Alami et al., 2023). The advancement of 3D printing technologies within the AM framework has further driven the transition from rapid prototyping toward the production of functional components (Hikmat et al., 2021). Additive Manufacturing encompasses various techniques, including Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF), Stereolithography (SLA), and

Selective Laser Sintering (SLS), each characterized by distinct processing mechanisms and application areas (Zhou et al., 2024). Among these methods, Fused Deposition Modelling (FDM) remains one of the most widely adopted technologies, particularly for prototyping applications, due to its flexibility, ease of operation, and relatively low production cost (S. Kumar et al., 2024).

One of the major limitations of FDM is its restricted build volume, particularly in desktop-scale printers, which prevents the fabrication of large components in a single printing process. As a result, objects with larger dimensions are commonly manufactured as separate sections that are subsequently joined to form the final product (Frascio et al., 2021). To address this limitation, components are divided into several sub-components and later reassembled, with adhesive bonding being one of the most widely applied joining methods (Silva et al., 2021). The use of adhesive bonding enables the development of lighter structural assemblies while simultaneously reducing stress concentration in the joint region (Zdravković et al., 2024).

The performance of adhesive joints is strongly influenced by the surface condition of the adherend. Surface preparation is intended to improve wettability and remove contaminants, thereby enhancing mechanical interlocking and increasing joint strength (Aliheidari & Ameli, 2024). One of the key parameters affected by surface preparation is surface roughness, which can be controlled through mechanical or chemical treatments (Ravichandran & Balasubramanian, 2025). In addition to surface characteristics, the type of adhesive employed also plays a critical role in determining the overall performance of the bonded joint (Bürenhaus et al., 2019).

This literature review aims to identify and analyse the adhesion mechanisms and the factors influencing the mechanical performance of single-lap joints in components manufactured using FDM. The review is expected to provide a more comprehensive understanding of the interrelationship among key parameters while also identifying existing research gaps that may serve as the foundation for future studies.

2. Additive manufacturing

Additive Manufacturing (AM), also known as 3D printing, is a rapidly advancing technology in modern fabrication that enables the efficient production of components with complex geometries in terms of both cost and processing efficiency (Nugroho et al., 2021; Zhang et al., 2022). This capability has accelerated its application in the fabrication of fibre-reinforced thermoplastic composites while also facilitating the integration of advanced materials with innovative structural designs (Cheng et al., 2023; Tian et al., 2022). In addition, AM offers high manufacturing flexibility with the potential for lower environmental impact compared with subtractive methods such as machining, particularly through improved material utilization and energy efficiency that support sustainable manufacturing practices (Colorado et al., 2020).

As summarized in Figure 1, AM processes can be classified according to various parameters, including machine dimensions, nozzle characteristics, deposition rate, and build volume. In addition, the classification may also be based on material type, energy source, geometry formation method, and supporting procedures. Nevertheless, the most commonly adopted classification approach is generally based on the type of material used in the manufacturing process (Abdulhameed et al., 2019).

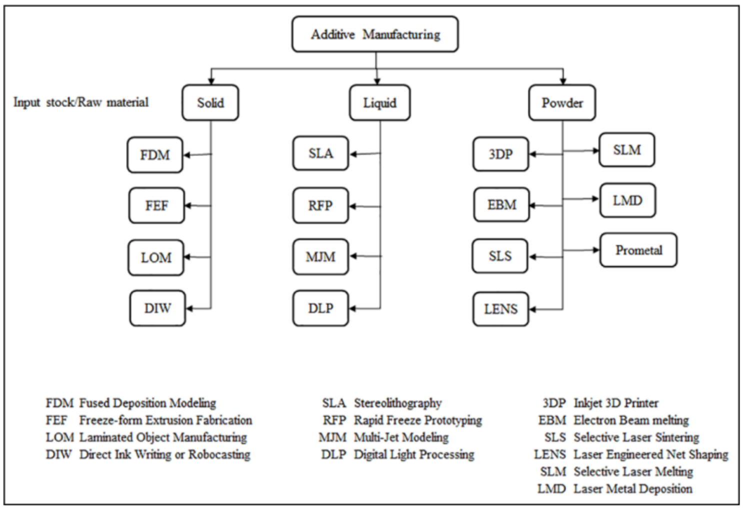


Figure 1. Classification of AM processes depending on the state of raw material (Abdulhameed et al., 2019)

AM encompasses a wide range of fabrication techniques that fundamentally differ from conventional manufacturing processes by constructing objects progressively in a layer-by-layer manner based on three-dimensional digital models. In general, the AM workflow begins with the development of a CAD model, followed by a slicing process that converts the geometry into thin two-dimensional layers. These layers are subsequently fabricated sequentially by the AM system until the final component is produced, as illustrated in Figure 2 (Sapkota et al., 2024).

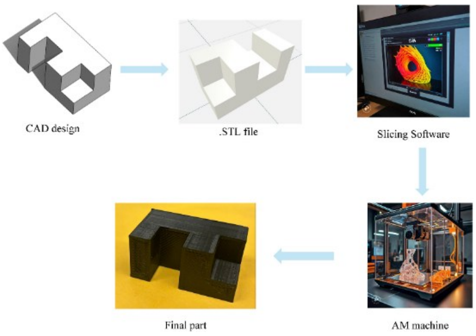


Figure 2. Schematic illustration of the Additive Manufacturing (AM) process flow, adapted from Sapkota et al. (2024)

3. Fused Deposition Modelling

As one of the principal methods in AM, FDM is an extrusion-based process used to produce three-dimensional objects through the layer-by-layer deposition of thermoplastic filaments (see Figure 3) according to digital design data (Efa & Ifa, 2025). Initially developed for rapid prototyping applications, FDM has evolved into a manufacturing technology for functional components across various sectors, including aerospace, automotive, and biomedical engineering. This development has been driven by its operational simplicity, relatively low production cost, and broad application flexibility (Golhin et al., 2023). Despite these advantages, FDM still faces significant challenges, particularly in achieving high printing speed, consistent mechanical strength, dimensional accuracy, and optimal surface quality (Singh et al., 2018). In addition, the limited build volume determined by the machine workspace restricts the fabrication of large-scale components in a single process. Consequently, large objects are commonly produced using a building-block approach, in which multiple sub-components are printed separately and subsequently assembled to form the final product (Morano et al., 2024).

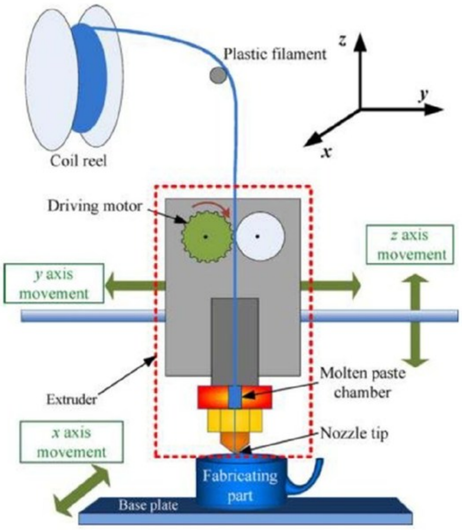


Figure 3. Schematic of illustration of the FDM 3D printing technology (Mishra et al., 2021)

In this context, the joining method becomes a critical factor in determining the structural integrity of FDM-manufactured components. One of the most widely applied approaches is structural adhesive bonding, which can produce continuous bonding between adherends without damaging the material properties. This method provides a more uniform stress distribution, a high strength-to-weight ratio, and additional functional benefits such as sealing and vibration damping (Pizzorni et al., 2025). Nevertheless, the material characteristics produced through the layer-by-layer deposition process in FDM introduce anisotropic mechanical behaviour due to weak interlayer bonding as well as the presence of internal voids and porosity (M. S. Kumar et al., 2023; Lambiase et al., 2023). These conditions become increasingly critical in bonded joint applications, where surface roughness generated by the stair-stepping phenomenon further influences adhesion quality and load transfer mechanisms at the interface (Ertürk et al., 2023; Sapkota et al., 2024). Consequently, the performance of adhesive-bonded joints in FDM components cannot be evaluated in the same manner as homogeneous materials. Instead, it is governed by the interaction between printing process parameters and adhesive-related characteristics, including printing orientation, interlayer bonding quality, surface condition, and adhesive layer thickness (Delia et al., 2024).

4. Adhesive bonding in structures

Adhesive bonding is widely employed for assembling 3D-printed components while also addressing the build-volume limitations of additive manufacturing systems (Tiwary et al., 2021). The effectiveness of the bonded joint is primarily determined by the quality of interactions at the adhesive–substrate interface, including adequate wetting behaviour and the formation of stable physical and chemical bonds. These conditions enable efficient load transfer across the joint, such that failure generally does not initiate at the interface when optimal adhesion is achieved (Ciferri, 2022; Pizzorni et al., 2025).

One of the primary adhesion mechanisms is mechanical bonding, which occurs through interlocking between the adhesive and the surface topography (see Figure 4). Surface roughness increases the effective contact area and enables the adhesive to penetrate micro-asperities, thereby strengthening the bonded interface (van Dam et al., 2020). Surface modification techniques such as sanding, etching, and abrasive blasting are commonly applied to enhance mechanical interlocking and improve the overall joint strength (Trentin et al., 2023). In addition to mechanical bonding, adhesion also involves chemical bonding and physical bonding as molecular-level interaction mechanisms. Chemical bonding, often referred to as primary bonding, occurs through the formation of covalent, ionic, or hydrogen bonds between the adhesive and the substrate. This mechanism provides greater strength and durability compared with mechanical interlocking alone (Dachev et al., 2025). However, the effectiveness of chemical bonding strongly depends on chemical compatibility and substrate surface conditions, often requiring surface treatment to improve surface reactivity and wettability (Jung et al., 2023).

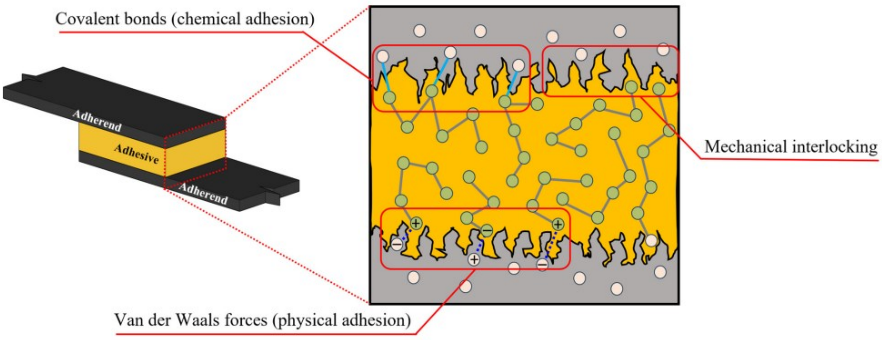


Figure 4. The different categories of bonding mechanisms (Dachev et al., 2025)

Components manufactured through the FDM process exhibit distinctive surface characteristics resulting from the layer-by-layer material deposition mechanism. This process produces a non-homogeneous morphology characterized by layer lines, stair-stepping effects, and the potential formation of internal voids and porosity (Maidin et al., 2023; Thumsorn et al., 2022). Such morphological features make the interaction between the adhesive and the substrate considerably more complex than in homogeneous materials, since the surface roughness inherently generated during the printing process may enhance mechanical bonding through physical interlocking mechanisms while simultaneously limiting wetting effectiveness and weakening chemical interactions at the interface (Naat et al., 2025; Parodo et al., 2025). Furthermore, the relative contribution of each adhesion mechanism is determined not only by the intrinsic properties of the adhesive but also by printing process parameters such as layer thickness, printing orientation, infill density, and the resulting surface topography (Tiwary et al., 2022). Consequently, the performance of adhesive joints in FDM-manufactured components cannot be evaluated using conventional approaches applied to homogeneous materials. Instead, it must be understood as the result of complex interactions among surface morphology, printing process parameters, and adhesive properties. Although increased surface roughness may be beneficial for mechanical bonding, irregular surface topography and limited wetting capability often introduce variability in joint strength. Therefore, understanding the relationship between FDM-generated surface characteristics and adhesion mechanisms remains an important research topic that continues to attract significant attention in recent studies.

5. Surface characteristics and roughness in FDM components

Components produced through the FDM process exhibit distinctive surface characteristics resulting from the layer-by-layer material deposition mechanism, leading to a non-homogeneous morphology characterized by layer lines, stair-stepping effects, and the potential formation of internal voids and porosity (Maidin et al., 2023; Thumsorn et al., 2022). These conditions introduce heterogeneity at the adhesive–substrate interface, which influences local adhesive distribution and load transfer mechanisms. Surface roughness generated during the manufacturing process may enhance bond strength through mechanical interlocking, as the adhesive can penetrate and interact with microscopic surface features. However, excessive or poorly controlled roughness may hinder the wetting process, restrict adhesive penetration into surface cavities, and promote the formation of interfacial voids, thereby reducing the effective contact area that contributes to joint strength (Parodo et al., 2025). These surface characteristics are not formed randomly but are governed by printing process parameters such as layer thickness, printing orientation, and infill density, all of which directly determine the quality of adhesive interaction at the bonded interface (Dachev et al., 2025; Tiwary et al., 2021).

As illustrated in Figure 5 reported by Jabłońska & Łastowska (2024), the PETG filament layers are arranged in a parallel configuration while partially interwoven at several locations. Under both layer-height conditions, impurities and inclusions appear as irregular reddish regions on the filament surface, which are believed to originate from filament imperfections carried during the deposition process. The presence of such impurities and voids on FDM surfaces should not be regarded merely as aesthetic defects, as they have direct implications for adhesive interface quality. These regions reduce the effective contact area between the adhesive and the adherend and may act as potential initiation sites for failure under shear loading.

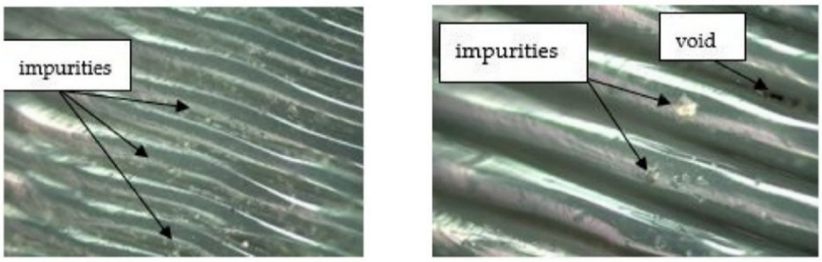


Figure 5. Microstructure of the surface of a sleeve manufactured by FDM (Jabłońska & Łastowska, 2024)

The surface characteristics produced by the Fused Deposition Modelling (FDM) process are not solely determined by the layer-by-layer deposition mechanism but are also significantly controlled by printing parameters, particularly layer height and printing orientation, both of which directly influence surface topography and quality. Variations in these parameters govern the distribution of surface asperities across different scales and therefore play an important role in establishing the initial conditions for adhesion (Golhin et al., 2023; Hawthorn et al., 2024; Kónya, 2024). An increase in layer height generally produces a rougher surface topology with larger asperity amplitudes due to the inherent characteristics of layered deposition in the FDM process (Mathew et al., 2023; Petruse et al., 2024). This condition may enhance mechanical interlocking by enabling deeper adhesive penetration into microscopic surface features (Mathew et al., 2023). However, the relationship is not linear, since excessive surface roughness may reduce the quality of surface contact and hinder uniform adhesive distribution at the interface. Furthermore, such conditions may increase the likelihood of void formation and reduce the effective contact area, meaning that joint strength does not necessarily improve with increasing roughness (Hawthorn et al., 2024).

The relationship between surface roughness and the functional properties of FDM-produced surfaces is inherently non-linear, as the resulting topography directly influences wettability characteristics (Amin et al., 2023; Golhin et al., 2023). Consequently, parameters such as layer height and printing orientation become critical factors in controlling surface conditions and interfacial interactions (Jabłońska & Łastowska, 2024; Nadeem et al., 2024). Accordingly, the performance of adhesive joints in FDM-manufactured components is not determined solely by material properties but rather by the complex interaction among surface topography, printing process parameters, and the adhesion mechanisms involved. Therefore, an integrated approach that simultaneously controls process parameters and surface characteristics is essential for achieving optimal joint performance.

6. Adhesive mechanisms in FDM-based joints

Understanding the adhesion mechanisms in FDM-manufactured components requires consideration of the layer-by-layer deposition process, which inherently produces structures with anisotropic properties and imperfections in interlayer bonding. FDM components commonly exhibit surface roughness, layered deposition patterns, and internal defects such as voids resulting from the limitations of the extrusion process, all of which directly influence interlayer bonding quality and mechanical performance (Omer et al., 2025). These characteristics are not merely passive features; rather, they actively determine how the initial contact between the adhesive and substrate is established and subsequently govern the evolution of adhesion mechanisms at the bonded interface. The quality of adhesive bonding is influenced by multiple factors associated with interfacial conditions, including surface characteristics, contact formation, and the presence of defects such as voids, all of which collectively determine joint performance (Dachev et al., 2025).

Surface roughness in FDM-manufactured components contributes to the development of mechanical interlocking mechanisms, as the surface topography enables the adhesive to penetrate and fill microscopic surface cavities (Bañón-García et al., 2024). However, the relationship between surface roughness and joint strength is not always linear, since excessive roughness may reduce contact quality and hinder uniform adhesive distribution at the interface (Bañón-García et al., 2024). In addition, surface wettability is another critical factor, particularly for materials such as PLA, which possess relatively low surface energy and may therefore limit adhesive spreading without additional surface treatment (Parodo et al., 2025). Furthermore, the presence of porosity and interlayer defects within FDM structures can compromise joint integrity by creating weak regions at the bonded interface.

In the single-lap joint (SLJ) configuration, the effects of these adhesion mechanisms become more significant because the shear stress distribution is inherently non-uniform and highly concentrated at the overlap ends. Imperfections in mechanical interlocking, limited wettability, and the presence of internal defects collectively intensify stress concentration in these regions, causing failure to initiate preferentially at locations with the lowest interfacial integrity (Manoj & Jain, 2025). Consequently, variations in surface characteristics and the structural quality of FDM components are directly reflected in the shear strength and failure modes of the bonded joint. Overall, the adhesion mechanism in FDM-based joints results from the interaction among surface roughness, wettability, and internal structural quality. These interactions govern the effectiveness of shear load transfer and control stress distribution within the joint, particularly in SLJ configurations. A comprehensive understanding of these relationships is therefore essential for interpreting the mechanical performance of adhesive joints, which will be discussed further in the following section.

7. Mechanical performance of single lap joint FDM-3D printed

The single-lap joint (SLJ) is one of the most widely used adhesive joint configurations due to its simple geometry and ease of experimental evaluation. Nevertheless, this configuration possesses an inherent limitation associated with its eccentric load path, which generates bending moments under tensile loading conditions. As a result, the adhesive layer is subjected to a combination of shear stress and peel stress, with stress concentrations typically occurring at the overlap edges (Liu et al., 2024; Wu et al., 2024).

In FDM-based joints, this stress distribution becomes more complex due to the anisotropic nature of the material and the presence of internal structural imperfections. Numerical analyses using the finite element method have been widely applied to evaluate stress distribution and failure mechanisms in FDM SLJ, revealing that failure frequently initiates in regions of maximum stress concentration near the overlap edges (Khosravani, Soltani, & Reinicke, 2021). Approaches such as cohesive zone modeling have also been employed to simulate crack initiation and propagation in FDM adhesive joints, with results demonstrating good agreement with experimental observations (Liu et al., 2024). Furthermore, modifications to joint geometry, including the introduction of stepped-overlap features or specific interfacial patterns, have been reported to reduce stress concentration and improve the load-bearing capacity of the joint (Khosravani et al., 2023).

The type of adhesive and the thickness of the adhesive layer are important parameters in determining the performance of SLJ. Adhesive thickness directly influences stress distribution within the bonded layer, where excessive thickness may increase deformation and promote localized stress concentration. Experimental studies have shown that there is an optimal range of adhesive thickness that provides improved joint performance in FDM-based structures, although the optimum value depends on the combination of materials and testing conditions employed (Öz & Öztürk, 2023). In addition, the selection of adhesive type has a significant effect on joint performance. Variations in adhesive mechanical properties, such as stiffness and ductility, can alter stress distribution patterns and influence the failure modes occurring within the bonded joint (Kamer, 2025).

Failure modes in adhesive joints are generally classified into adhesive failure, cohesive failure, mixed failure, and substrate failure. In FDM-based joints, these failure modes arise as a consequence of interfacial conditions, material properties, and stress distribution during loading (Khosravani et al., 2023). Adhesive failure occurs at the adhesive–substrate interface due to weak chemical bonding, which is commonly caused by contamination, inadequate surface preparation, or premature curing of the adhesive before optimal bonding is achieved (see Figure 3a). Service-related factors such as fatigue, creep, and peel stress may further accelerate the occurrence of this failure mode. Cohesive failure occurs within the adhesive layer itself and is characterized by adhesive residue remaining on both bonded surfaces. This failure mode is generally associated with the combined effects of shear and peel stresses, as well as non-optimal joint design factors such as insufficient overlap length, non-uniform stress distribution, or the presence of porosity (see Figure 3b). In contrast, substrate failure occurs when the strength of the base material is lower than the bonding strength, causing damage to propagate within the adherend rather than at the bonded interface (see Figures 3c). This condition is commonly observed in materials that are thin, brittle, or structurally degraded (Omairey et al., 2021).

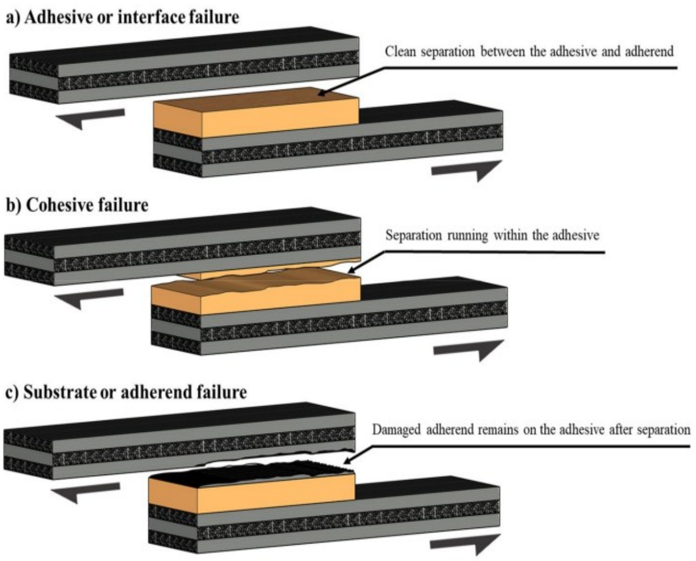


Figure 6. The main three modes of adhesive bond failure: (a) Adhesive or interface failure, (b) Cohesive failure, (c) Substrate or adherend failure (Omairey et al., 2021)

Overall, the mechanical performance of single-lap joints is not determined solely by the maximum shear strength but also by how stresses are distributed and interact with surface conditions and material characteristics during loading. Non-uniform stress distribution, particularly the concentration of shear and peel stresses at the overlap edges, represents a key factor governing damage initiation and the subsequent evolution of joint failure. In this context, failure mode analysis becomes essential for identifying the dominant mechanisms controlling structural response while also evaluating the effectiveness of the applied design and processing parameters.

8. Fundamental mechanics of load transfer and stress distribution in FDM-based single-lap joints

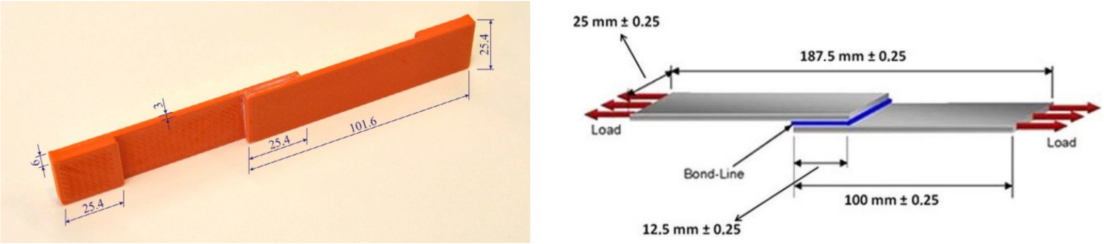
When a SLJ is subjected to uniaxial tensile loading, the resulting load path becomes eccentric due to the misalignment between the line of action of the applied force and the joint interface. This condition inherently induces a bending moment that promotes joint rotation and generates a combination of shear and peel stresses at the adhesive interface (Manoj et al., 2024; Manoj & Jain, 2025). Within this mechanism, the load is not transferred directly between the adherends but is instead transmitted through the adhesive layer, which acts as the primary load-transfer medium, with shear stress serving as the dominant stress component, particularly within the overlap region (Manoj et al., 2024). However, stress distribution along the overlap is never completely uniform. Stress concentrations tend to develop near the overlap edges due to eccentric loading effects and deformation incompatibility between the adherends. This condition becomes more critical in joints composed of dissimilar adherends, where the adherend with lower stiffness undergoes greater deformation and carries a higher proportion of the applied stress. As a consequence, load transfer becomes less efficient and may trigger premature damage initiation, which subsequently propagates into progressive failure along the bonded interface (Manoj & Jain, 2025).

Damage in adhesive joints generally initiates within the overlap region due to the high peel stresses concentrated near the overlap edges. These stresses arise from sharp stress gradients caused by the combined effects of geometric discontinuity, associated with sudden changes in stiffness, and load eccentricity, which induces local bending moments. In the study conducted by Khosravani et al. (2023), numerical analysis revealed that the maximum von Mises stress was localized at the outer vertical edges of the adhesive layer, both on the upper and lower sides, corresponding to the initial locations of cohesive failure. However, this stress distribution is not fixed, as geometric modifications such as stepped-lap configurations can gradually reduce stiffness discontinuities, thereby lowering stress concentration at the overlap edges and promoting a more distributed load transfer mechanism without completely eliminating the stress source. The relevance of this phenomenon in FDM adherends lies in the coincidence between stress concentration at the overlap edges and the inherently weak interlayer bonding within printed structures, making these regions the dominant sites for failure initiation. Rajesh et al. (2024) demonstrated that overlap geometry modifications, such as joggle and wavy configurations, were capable of redistributing stresses away from these critical zones, reducing local stress concentration, and shifting the failure mode from adhesive to cohesive failure. As a result, these modifications directly improved the load-bearing capacity and structural integrity of the bonded joints.

The shear strength of SLJ-FDM results from the systemic interaction among adhesive properties, geometric distribution, and interfacial quality. Differences in adhesive modulus and ductility govern stress distribution behaviour, where stiff adhesives tend to concentrate stresses at the overlap edges, whereas ductile adhesives promote more uniform stress redistribution and delay failure initiation. This principle has been validated in bi-adhesive configurations, in which a ductile adhesive placed near the overlap edges reduces stress concentration, while a brittle adhesive positioned in the central region maintains load-bearing capacity. Nevertheless, the effectiveness of this approach remains strongly dependent on the interfacial quality produced by the FDM process. When adhesion strength is insufficient, failure tends to occur at the interface, thereby eliminating the benefits of engineered adhesive distribution (Demir & Yüksel, 2025). FDM adherends are inherently constrained by printing-direction anisotropy and the presence of internal voids, both of which weaken interlayer bonding and make the mechanical response highly dependent on loading orientation. This combination produces non-homogeneous mechanical behaviour that challenges the isotropic assumptions commonly adopted in conventional joint analysis. Consequently, the performance of FDM joints must be evaluated as the result of coupled interactions among printing orientation, void distribution, and loading conditions (Equbal et al., 2024).

9. Measurement, parameter sensitivity, and mechanical interpretation of shear strength in FDM-based single-lap joints

The evaluation of adhesive joint strength in SLJ configurations generally refers to two primary standards, namely ASTM D1002 and ASTM D3163. ASTM D1002 was originally developed for metal-to-metal adhesive joints and provides the parameter of apparent shear strength, which is essentially comparative in nature due to the inherent limitations of the eccentric SLJ geometry that generates combined stress responses. In contrast, ASTM D3163 was specifically designed for adhesive bonding in rigid plastic materials, making it more suitable for polymer-based systems such as PLA used in FDM manufacturing. Although both standards adopt similar lap shear configurations, differences in material domain and underlying testing assumptions mean that the resulting data cannot be directly compared without considering the effects of material properties, interfacial conditions, and fabrication process variables. Therefore, the application of these two standards in research should be regarded as complementary approaches rather than interchangeable testing methods (ASTM D1002-10, 2019; Khosravani, Soltani, Weinberg, et al., 2021).



(a) (b)

Figure 7. (a) ASTM D3163-01 geometry design in millimeters ((Khosravani, Soltani, Weinberg, et al., 2021), (b) Lap-shear test load path (Latko-Durałek et al., 2022)

In SLJ testing, loading eccentricity and misalignment can introduce peel stresses, meaning that the apparent shear strength measured according to ASTM D1002 does not represent a pure shear condition. Consequently, differences in strength observed under varying conditions, such as changes in FDM printing parameters, do not necessarily reflect the intrinsic shear capacity of the joint but may instead be influenced by the specimen's sensitivity to uncontrolled peel stress components. This observation is consistent with the parametric study reported by (Chen et al., 2022), which demonstrated that increasing overlap length and adhesive thickness unexpectedly reduced joint strength by approximately 53.83% and 16.15%, respectively. This reduction was attributed to stress redistribution effects that intensified the contribution of peel stresses at the overlap edges.

Printing orientation is one of the most fundamental parameters in FDM-based SLJ systems because it directly determines the load transfer path and the location of structural weaknesses. At a 0° orientation, the filaments are aligned parallel to the loading direction, allowing the load to be transmitted through relatively continuous filament bodies. This configuration results in the highest load-bearing capacity and shear strength, as reported in studies on FDM-based SLJ structures that identified optimum performance under this orientation (Hiremath et al., 2024). In contrast, at a 90° orientation, the load is forced to pass across interlayer interfaces, which are inherently weaker due to incomplete diffusion bonding and the presence of voids. Consequently, the failure mechanism is dominated by interlayer delamination (Güneş et al., 2026). As a result, tensile shear strength may decrease by approximately 47% compared with the 0° orientation, accompanied by a more brittle deformation response caused by the limited plastic deformation capability in the direction perpendicular to the deposited layers (Hiremath et al., 2024).

Overlap length and adhesive thickness influence joint performance through different mechanisms. An increase in overlap length may actually reduce shear strength because the majority of the applied load is carried by the overlap edges, while the central region contributes minimally to load transfer. As a result, extending the overlap does not proportionally increase the load-bearing capacity of the joint (Chen et al., 2022). Surface roughness also exhibits a non-linear relationship with joint strength. Peak performance is generally achieved at moderate roughness amplitudes, whereas excessive roughness can create localized geometric defects that act as crack initiation sites (Hiremath et al., 2024).

Mechanistically, the performance of SLJ-FDM results from the interaction among stress distribution, material anisotropy, and interfacial adhesion quality. The study by Rajesh et al. (2024) demonstrated that modified overlap geometries, such as joggle and wavy configurations, increased load-bearing capacity by approximately 65.91% and 55.45%, respectively, compared with conventional designs. These improvements were achieved not through changes in material properties, but because the modified geometries altered the load transfer path and reduced stress concentration at the overlap edges. More importantly, the key effect of these geometric modifications is not merely the redistribution of stresses, but the delay of damage initiation and the reduction of crack propagation rates. Consequently, failure no longer occurs prematurely in localized regions, allowing both the material and the adhesive interface to sustain higher loads more effectively. Adhesion quality determines the location and mode of failure, whether adhesive or cohesive in nature. However, Ribeiro et al. (2026) emphasized that in SLJ-FDM systems, failure behaviour is also strongly influenced by the interaction between adherend anisotropy and the local stress field. In this context, the Cohesive Zone Model (CZM) serves not only as a predictive tool but also as a critical analytical approach because it can capture progressive damage initiation, crack propagation, and failure mode transitions, phenomena that cannot be adequately explained using conventional strength-based approaches alone.

10. Conclusion

This review demonstrates that the mechanical performance of adhesive joints in Fused Deposition Modeling (FDM) components, particularly in single-lap joint (SLJ) configurations, cannot be separated from the complex interaction among surface characteristics, adhesion mechanisms, and loading conditions. FDM structures produced through layer-by-layer deposition inherently exhibit material anisotropy, surface roughness, and internal defects such as voids and porosity, all of which directly influence the quality of adhesive–substrate interactions and the effectiveness of load transfer. Adhesion mechanisms in FDM joints are governed not only by mechanical interlocking resulting from surface topography but also by wettability and the formation of physical and chemical bonds at the interface. The relationship between surface roughness and joint strength is non-linear, where increased roughness may enhance interlocking up to a certain limit but can also reduce contact quality and adhesive distribution if not properly controlled. Consequently, printing parameters such as layer height and printing orientation play a critical role in determining the initial conditions for adhesion formation.

Within the mechanical context of SLJ structures, the eccentric load path generates a combination of shear and peel stresses that are unevenly distributed, with stress concentration occurring at the overlap edges as the primary site of failure initiation. This phenomenon becomes more complex in FDM materials due to anisotropy and internal structural imperfections, making the assumption of homogeneous material behaviour in conventional analyses less representative. The shear strength values obtained from standard tests such as ASTM D1002 and ASTM D3163 fundamentally represent a combined stress response rather than pure shear loading. Therefore, the interpretation of test results must consider the contribution of peel stresses and specimen-specific conditions.

Furthermore, design and process parameters, including printing orientation, adhesive thickness, overlap length, and joint geometry modification, have been shown to influence stress distribution and load transfer paths significantly. Variations in these parameters not only alter the maximum joint strength but also control damage initiation sites and the resulting failure modes. In this regard, mechanics-based approaches, including numerical modelling techniques such as the Cohesive Zone Model (CZM), are essential for understanding failure behaviour more comprehensively than approaches based solely on strength values.

Overall, this review confirms that the performance of adhesive joints in FDM systems results from coupled interactions among surface morphology, interfacial adhesion quality, material properties, and stress distribution during loading. Therefore, joint optimization cannot be achieved by focusing on a single parameter independently but instead requires an integrated approach that considers the interdependence among these factors. Although numerous studies have provided insight into individual aspects of FDM adhesive bonding, significant limitations remain in integrating surface characterization, adhesion mechanisms, and mechanical response within a unified analytical framework. This gap presents important opportunities for more comprehensive and targeted future research.

Author's declaration

Author contribution

Muhamad Qeisya Hanif: Conceptualization, Literature search and screening, Data curation, Writing – original draft, Writing – review & editing. **Rifelino**: Supervision, Conceptualization, Writing – review & editing, Validation. **Febri Prasetya**: Writing – review & editing, Validation, Methodology. **Zainal Abadi**: Writing – review & editing, Validation.

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Data availability

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Conflict of interest

The authors declare that there are no conflicts of interest related to this research or the publication of this article.

Ethical clearance

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AI statements

ChatGPT, Gemini, and Claude.ai were used to improve the grammatical structure, sentence coherence, and translation of this article from Indonesian into English to enhance readability. All AI-assisted outputs were carefully reviewed by the authors to ensure their accuracy, precision, and contextual relevance to the research topic and data presented. The authors take full responsibility for the entire content of this article.

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