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A review: Assessment of the Theories of Fundamental Mechanisms, Designing, and Failure on Structural Adhesive Joints Bond

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Abstract

Adhesives have been around for millennia. Nevertheless, this technique for joining has only seen significant development within the past 70 years. Professional technical engineering applications primarily use adhesives derived from synthetic polymers, a development that dates back to the mid-1940s. Its characteristics facilitate their strong adhesion to most substrates, as well as their ability to transfer substantial loads. This paper presents an extensive assessment of the current knowledge in the field of adhesives and related technologies, with a focus on adhesion theories and their parameters, as well as designing, joint configuration, geometric aspects, and failure modes. The paper also explores the interplay between research and development efforts, industrial standards, and regulatory aspects, with the goal of fostering collaboration between academia and industry. Over the past years, the development of new materials, methods, and models has resolved many of the shortcomings. Nonetheless, it is still possible to evaluate and estimate the optimal combination of aspects that will give the greatest efficiency and performance for adhesive bond joints (ABJs).

1. Introduction

Nowadays, the adhesive bond joints ABJs are an element of the essential assembly technologies in the fabricating and synthetic industries. It serves extensively to tiny, small, Mid-sized and massive structures for instance in furniture, Application-Specific Integrated Circuits ASICs, automobiles, aircraft, aerospace, wind turbines, ship hull structures. Furthermore, may be combined with other fastening methods mechanics to enhance it is effectiveness. Consequently, the durability and strength of the adhesive bonding influence the elements and entire system strength. Owing to the advantages resulting from the use of adhesives, the use of their integration is rapidly increasing in various industries, as these functionally graded materials (FGMs) have provided multi-functional spread in different human needs in daily life [1].

Massive structures that are conventionally loaded, for instance marine structures and bridges, exhibit the problem of excess weight, and corporations aspire to seek for durable and reliable solutions and technologies to reduce their weight without compromising their mechanical properties and withstanding various loads and harsh environmental conditions. Moreover, in other similar structures, such as aerospace applications and automobiles, there is also a need to reduce weight, as reducing weight by 10% can lead to reducing fuel consumption by 8%, ABJs Joining techniques based on sustainable composite materials are the best solution to reduce energy consumption and achieve greater environmental benefits [2-3]. This has stimulated the economic industrial sector to explore for lightweight composites materials that have the strong capability to withstand high loads and ensure safety. Combining metals and composite materials can minimize weight whereas maintaining strength, leading to High-strength low-weight materials. Adhesives are the most suitable bonding technique for joining various stress-prone materials when compared to other classical joining techniques, such as welds, screws, bolts, nails, and rivets [4]. In general, the following unique key points can be identified through comparison:

1. The adhesive-bonded joints (ABJs) allow for the efficient joining of similar or dissimilar adherent materials devoid of the need for fabrication or destruction of the joint adherent material. This is particularly useful for lightweight materials that aim to create lightweight structures.
2. The modulus of elasticity of adhesives is generally approximately between 2 and 7 GPa, which is substantially less than the adherent’s modulus of 20-200 GPa (assuming the free form of several materials with negligible modulus figures). Therefore, the aforementioned and obvious distinction can significantly influence the mechanical characteristics and component features of an ABJ's structure.
3. The energy transmission method and principal loading mode between the adhesive and an adherent is shearing stress that is generally substantial than the energy elements and peel load. Additionally, deformations caused by bending may result in increased peel stress when Adhesive

Bond Joint ABJs applied to Minimal-Wall Thickness Structures MWTSs [5].

4. Crack initiation in joints as a result of stresses (peel and shear) existence concentrated and singularity at the edges on the bonded joint; furthermore, accurate stress analysis possibly finds numerical complications, and stress founded on a strength approach is unlikely to be utilized to estimate adhesive joints failure [6].
5. The most popular technique for bonding (MWTSs) uses lap joints (single or double) to distribute loads in the components. Lap joint eccentric loading is a significant difficulty in mechanical analysis owing to geometric non-linear behavior [7].

For the above motives, many studies have been carried out for studying mechanical properties, features, characteristics, design, manufacturing process, experiments, theoretical modeling, and structural analysis under variant service conditions and environments. Since, many scientific fields for instance Geometric, Physical, and Chemical are included in the study of ABJs, Consequently, to investigate this application in the literature, the researcher may find many parameters such as behavior, properties, components, and different techniques used in synthesis, so there is no single point that may this bonding technology started off from it. To clarify previous reviews works, a comprehensive assessment of literature from previous years to the present can be reviewed in Table.1. In this regard, it is important to emphasize that the reviews shown in the table are regarded as the most significant research published for each decade up to the present.

Notably, literature evaluations have mostly focused on one feature of ABJs as a topical aim, addressing a particular issue within the field, apart from some reviews, in particular Banea and da Silva [8], in 2008 they performed a detailed assessment of ABJs for composite structures. Joint configurations, Surface preparation, adhesive behavior, and environmental factors all affect the mechanical performance of ABJs in Fiber-reinforced polymer FRP structures. Budhe et al. in 2017, [9] provided an update of the previously mentioned subjects of review. The literature has included many subject studies that investigated adhesive joints from different points of view. Table 1 includes these summaries.

Eventually, at present, Wei et al. in 2024, [5] provided a comprehensive review on the design and manufacturing of adhesively bond joints ABJs, focusing on the design, fabrication, and modeling experiments of adhesive joints, assessing the challenges of this field. The review covers developments from 2016 to 2023 and discusses adhesives, manufacturing techniques, and defect detection methods. Furthermore, it assesses the efficiency of adhesive joints and reviews the engineering applies of these joints. This provides an important update on current research and future challenges in this field. Figure 1 illustrates a thorough summary and major advancement pertaining to the mechanical design of ABJs.

To facilitate the interested researchers with a thorough, comprehensive overview of several research topics on (ABJs), this paper aims to present the various literatures related to adhesive-bonded joints in a comprehensive manner, enabling future researchers to view and understand the wide range of topics in this field, also provide recommendations for future research in this area.

1.1. Terminology

It is important to note the definitions of certain terms in the field of research.

Adhesive: A substance adheres two or more surfaces together by filling the gap between them, forming a strong, cohesion bond (i.e., creating “adhesion” between them) through chemical or physical interactions. It can be formed into a liquid, gel, or solid [40].

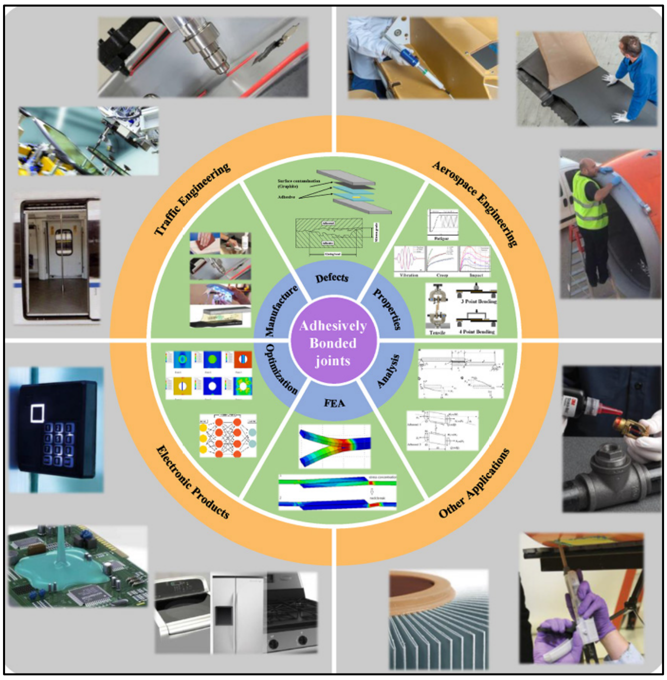


Fig. 1 Shows the framework for a cutting-edge assessment of ABJs [4].

Adherend: Often called a substrate, it serves as a basic material or surface for applying adhesives or other covering materials [40]. The substrate can consist of various engineering materials, such as metals, polymers, ceramics, and composites assembled from any of these materials [41]. The substrate's characteristics, including its roughness, bonded area, surface treatment type, and adhesive compatibility, significantly influence the bonding process's efficacy [42].

Adhesion: refers to the mutual attraction between two substances, which, once combined, requires effort to separate them. Conventional definition excludes magnetic attractions [40].

Overlap: refers to the area where the adhesive completely covers the two surfaces, establishing their connection. For instance, the overlap in a single lap joint refers to the length at which the adhesive interface joins the two parts. The design of adhesive joints heavily relies on overlap, which directly influences the joint's mechanical load capacity, stiffness, and stress distribution. Common measurements of overlap are given in units such as length (e.g., mm) or area (e.g., mm^2).

Curing: During its initial stages of application, an adhesive must exist as a liquid to facilitate wetting and spreading over the adherent. Yet it must eventually solidify. Regardless of the method, it refers to this transition from liquid to solid as "curing" [43]. Adhesive curing refers to the processes of polymerization and cross-linking used to achieve certain bond strengths. Curing is a critical procedure for accessible, optimal bonding properties [44]. Three distinct stages make up the curing process: initial, basic, and post-curing [5].

Phase: distinct forms of matter exist, like solids (crystalline, amorphous, etc.), liquids, or gases (vapors). A phase-change material (PCM) distinguishes itself from the state of matter [45].

Pre-treatment: Preparing the substrate surface improves the durability, strength, and life cycle of the adhesive bond. Occasionally, a suitable preparation may bestow additional characteristics on surfaces. Creating an appropriate surface chemistry is a crucial stage in the surface preparation procedure, as the strength of this surface directly influences the durability and service life of the adhesive bond, as stated by Davis and Bond [46]. It is advisable to perform surface treatments prior to applying adhesives to get optimal mechanical strength [47].

Solvent based: This definition only refers to solutions made in an organic solvent, not aqueous (water)-based solutions. It also includes materials or processes that use a solvent (liquid) to thin out or dissolve a substance, like adhesives or coatings [48], [49].

Table 1. overview of the key evaluations of adhesive technology from the last few decades to the present.

Literatures	Scope
Kutscha, 1964, [10]	Comprehensive review of the design, mechanical properties, failure criteria, experimental design techniques, and theoretical, experimental analysis of lap-type joints.
Murphy et al., 1974, [11]	Comprehensive review of the literature on stress analysis in welded, riveted, and ABJs. An annotated bibliography of papers public shed from 1968 to 1974 on this topic is presented, with an emphasis on the analysis of stresses in multilayered materials (isotropic and anisotropic).
Matthews et al., 1982, [12]	Comprehensive review of the strength of ABJs, it compares standard analytical approaches to finite element methods FEM for investigating adhesive joints, while also providing general design principles and analytical foundations for stress distribution.
Guyott et al., 1986, [13]	A comprehensive review of non-destructive testing (NDT) processes for ABJs and the types of flaws that can be detected using those techniques.
Adams and Cawley, 1988, [14]	Comprehensive review of the types of defects in composite materials and adhesives, reviewing NDT techniques used to detect those defects.
Satoh et al., 1996, [15]	The Committee on Adhesive Bonds in Automotive Structures (ABAS) conducted a comprehensive review. It continued for five years, starting in 1989, with the aim of developing structural adhesive technology in automobile bodies in Japan, noting the importance of estimating the reliability of ageing and impact tests.
Allen, 2003, [16]	Comprehensive review of the development of adhesive science over the past forty years. The study reviews significant progress in fundamental theories of adhesives, particularly in the concept of mechanical bonding, adhesive mechanism, Adhesion, cohesion forces, and polymer spread, along with pressure-sensitive adhesives and weak boundary layers. Furthermore, these theories have evolved over time, with an emphasis on the practical and industrial advancements that have resulted from these developments.
He, 2011, [17]	Comprehensive review on FEM analysis of ABJs, focusing on applications of the analysis under different conditions particular in static and fatigue loading
Katnam et al., 2013, [18]	Scientific review on the repair of aircraft composite structures applying adhesives, focusing on the technical challenges and potential opportunities in this field. The review provides a framework for improving adhesive repair techniques and highlights the need for additional research to improve the reliability of repairs under challenging environments.
Pethrick, 2014, [19]	Comprehensive review of the design of ABJs and the environmental influences on their performance over time focuses on the design of adhesives used in structural bonding and the effects of aging on them, as well as the impact of environmental determinants such as moisture, temperature, and atmospheric pressure on the long-term performance of ABJs.
Heshmati et al., 2015, [20]	Comprehensive review on the durability of ABJs, particularly in issues related to environmental degradation of these joints. It also reviews the most important influencing factors such as moisture, temperature, and long-term mechanical stresses. The paper not only provides data from durability tests conducted on materials used in civil engineering applications, but also highlights areas for future research that require attention.
Machado et al., 2017, [21]	Comprehensive overview of the behavior of ABJs under impact loading, an active field due to significant industrial interest. Furthermore, it focuses on the use of ABJs in industries, for instance, automotive and defense, which require high impact resistance to ensure structural integrity.
Jeevi et al., 2019, [22]	Comprehensive review provides a detailed review on the application of ABJs in hybrid composite structures. However, it also discusses a range of factors that affect these joints' performance, including surface treatment methods, joint design, material properties, and environmental conditions such as moisture and temperature.
Shang et al., 2019, [23]	Comprehensive review of techniques for improving the strength of ABJs in composite structures, with an emphasis on factors affecting performance such as modification of geometric and material properties.
Gursel and Cekirge, 2019, [24]	Comprehensive review on the behavior of ABJs under impact loading. The study delves into the significance of ABJs in impact-prone engineering applications, especially in the automotive sector, where they serve to decrease automobile weight by joining lightweight, multi-layered materials. The focus is on the distinctions in adhesive joint performance under quasi-static and impact loads, emphasizing the significance of testing methods and the role of strain rates in determining performance.

Ramalho et al., 2019, [25]	Comprehensive review focuses on various methods for predicting the strength of ABJs under static load. The study addresses both analytical and numerical approaches used to evaluate the strength of ABJs, with a particular focus on the application of Cohesive Zone Models (CZM) as the most common and accurate method for predicting durability. Furthermore, the study conducts a comparison with traditional join analysis methods.
Ramírez et al., 2020, [26]	Comprehensive review on the impact of environmental degradation such as temperature and moisture on the fatigue failure performance of ABJs. Furthermore, it discusses experimental work and analytical models that have been developed to study this topic and presents the most important developments and limitations in this field.
Bukhari et al., 2020, [27]	Comprehensive review on the influence of surface roughness on wetting intensity and energy in ABJs made of polymers. It talks about theories of adhesion. It also discusses industrial applications of adhesive joints in lightweight structures, such as making aircraft and automotive.
Abid et al., 2020, [28]	The review examines how the preparation surface affects the strength of AL 6061 T6 aluminium ABJs. It explains that increasing surface roughness leads to an increase in bond strength up to a specific limit, but if the roughness increases excessively, the strength begins to decrease.
Marques et al., 2020, [29]	Comprehensive review aims to provide an overview of recent developments in adhesive technologies and surface treatments for structural applications, with a particular focus on developments related to sustainability and applications in metal and composite structures.
Kanani et al., 2020, [30]	Comprehensive review delves into the various applications of joining different materials, such as metal and composites, using adhesive and hybrid joints. Additionally, it discusses the failure mechanisms of these joints under the influence of structural loads and environmental conditions and reviews the efforts made to improve their performance through engineering and material modifications.
Kupski and Teixeira de Freitas, 2021, [31]	Comprehensive review on the design of carbon fiber reinforced polymer (CFRP) adhesive joints as well as their applications in aerospace structures. It focuses on designs of adhesive joints and challenges related to these joints; hence, it suggests prospects to improve their performance and reduce the possibility of early failure.
Omairey et al., 2021, [32]	Comprehensive review of the limitations and challenges facing ABJs in composite structures. This research offers a study of the primary issues associated with adhesive joints, including defects that arise from inadequate contact between adhesive surfaces (e.g., bonding interfaces, air bubbles, and delamination), as well as defects resulting from environmental and manufacturing degradation. It also highlights the challenges associated with identifying these defects through conventional non-destructive methods, as well as their impact on the durability and efficiency of ABJs, particularly in harsh environments.
Wang et al., 2021, [33]	Comprehensive review delves into the research and experiments that investigate the fracture of ABJs between dissimilar materials. It focuses on analyzing the cracks in these joints, discussing three main aspects: mechanical tests, factors leading to crack growth, and mixed mod fracture (mode I and II). Furthermore, it demonstrates how to improve performance using new techniques and crack analysis in adhesive joints between dissimilar materials, indicating the need for more experiments to verify the proposed theories.
Maggiore et al., 2021, [34]	Comprehensive review discusses the various techniques used to achieve durable and stress-resistant joints in hybrid bonding processes, focusing on structural adhesive joints specifically. It highlights the role of structural adhesives like epoxy and polyurethane in enhancing structural performance across a range of applications, including the aerospace and automotive sectors.
Delzendehrooy et al., 2022, [35]	Comprehensive review on structural bonding technologies in the marine industry, including adhesive, welding, mechanical, and hybrid bonding. Each technique's pros and cons are discussed, with an emphasis on choosing the best one for the industrial application and its needs. The research underscores the significance of hybrid bonding, a technique that blends two distinct technologies to enhance performance efficiency and endure the severe conditions these structures encounter in marine environments.
Akhavan-Safar et al., 2022, [36]	Comprehensive review of the applications of ABJs in various industries, with a focus on the benefits and challenges of their manufacture and use. The review demonstrated that using adhesive joints with two types of adhesives (brittle and ductile) substantially improves joint strength while decreasing the total weight of the structures.
Desai et al., 2023, [37]	The review provides a thorough analysis of methods to enhance ABJ's strength and fracture standards, highlighting the influence of geometric design and material characteristics on structural efficiency. The study focuses on enhancing the strength of ABJs by applying a variety of geometric design techniques, stress distribution, and material arrangement. Additionally, it employs mechanical fracture testing methods to gauge fracture characteristics and assess the overall performance of adhesive joints.
Dallaev, 2024, [38]	Comprehensive review on recent developments in the field of materials with self-healing properties. It discusses materials, including polymers, ceramics, metals, and composites, that can self-repair damage with little or no external intervention. Also, review the diverse applications of these materials in fields such as aviation, marine industry, medicine, and engineering. The mechanisms of crack healing and damage healing in structures, which contribute to extending the life of materials and reducing maintenance costs, receive emphasis.
Yao et al., 2024, [39]	Comprehensive review on the fatigue behavior of soft adhesive systems (SASs), which are widely applied in industries such as biomedicine, flexible electronics, and robotics. It systematically reviews the mechanisms behind fatigue failure in SASs, including energy dissipation during cyclic loading. It highlights classical research methods like total fatigue lifetime and fatigue crack growth (FCG) to understand these failures. Furthermore, the study outlines unresolved issues in predicting the service life of SASs under complex load conditions. Importantly, the study examines the role of soft properties like viscoelastic dissipation in relation to fatigue failure mechanisms.

High/low energy surfaces: Typically, metal surfaces (or their oxides) have high energy levels ranging from 200 to 1500 mJ.m^{-2}, while most polymers have low energy levels with values between 20 and 50 mJ.m^{-2}. Water has a numerical value of 72 J.m^{-2}, which is unusual [50].

Wetting: is the degree of intimate contact that a liquid establishes with a surface upon application. The distribution may vary from complete coverage across the surface to the presence of droplets with minimal or no contact. The term contact angle θ, serves to elucidate this concept. A strong adhesive bond can only be achieved through effective adhesion wetting by an adhesive, which is a necessary but insufficient condition [40], [50]. Figure 2 illustrates some of the above terms and the structure of ABJ in relation to a single lap joint (SLJ).

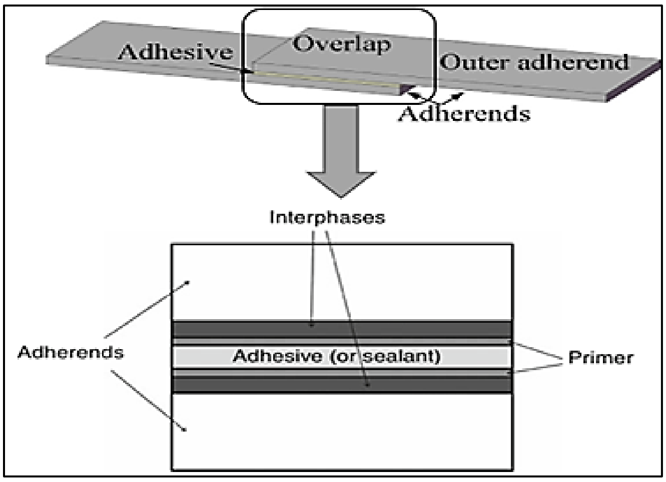


Fig. 2 the Adhesive Bond Joint, which includes the adhesive, adherend, and overlap in SLJ [5], [50].

2. Fundamental of adhesion

The study of adhesion, including its mechanisms and theories, has only recently begun in a significant way. The Adhesives Research Committee of the British DSIR noted in 1922 that there was no single method that could account for all accepted explanations for the mechanism by which adhesives bond surfaces. Over the last 80 years of the century, several explanations and ideas have emerged. Initially, many mistakenly believed that a single explanation could and should explain every instance of adhesion, from attaching a postal stamp to an envelope to providing the necessary strength for an airplane's construction. In the end, this assumption's lack of logic led to the creation of many theories, each of which can explain a wide range of adhesion situations on its own or in combination with others [40], [51].

2.1. Adhesion theories (Mechanisms)

Researchers have developed numerous theories to study the formation of bonds, like mechanical interlocking, diffusion, electrostatic/electronic, and physical absorption [52]. Also, Van der Leeden and Frens [53] categorize adhesion models into four primary groups: mechanical, diffusion, electrostatic, and adsorption theories. Fourche [54] suggests a like classification based on the idea of weak border layers. Although some have questioned this idea [55], it still helps explain certain cases of weak adhesion. This section will provide important reviews of each mechanism individually, which can aid in understanding the formation of the adhesive bond.

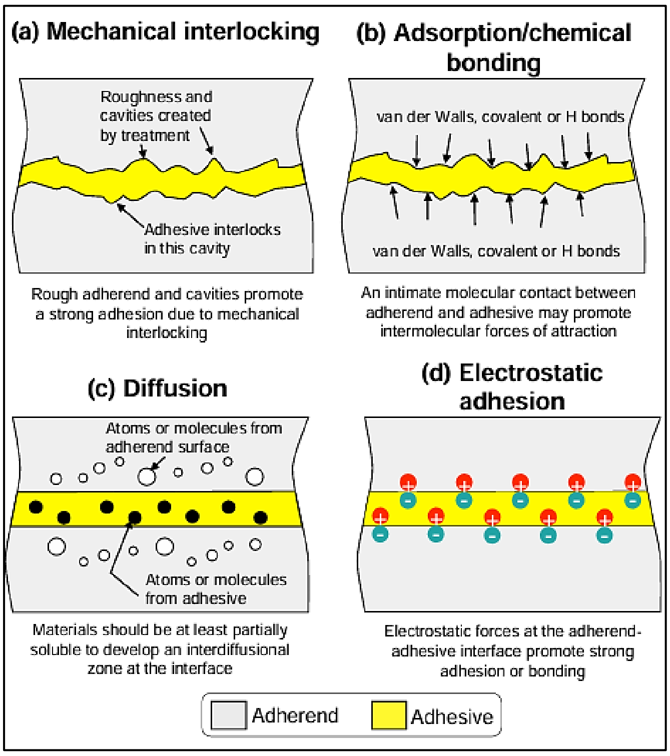


Fig. 3 Adhesion theories [52].

2.1.1. Mechanical interlock theory

It is a fundamental concept that represents the earliest explanation of adhesion. McBain and Hopkins proposed it in 1925 [51]. Occasionally referred to as "hooking," this process entails the liquid adhesive penetrating the crevices and flaws of a solid adherent surface and subsequently hardening within those spaces. After curing, the interface establishes the meshing connection, or anchoring effect. The mechanical interlocking concept primarily relies on the adhesion's roughness and the adhesive's porosity [56]. Figure 4 (a) to (e) displays various conventional mechanical connection models. Figure 5 shows sufficient and poor wetting. Mechanical interlocking significantly influences the adhesion of fibrous or porous materials to steel [55], including wood [57], textiles [58], paper, and natural rubber [55]. Later, other studies [59-61] showed how important it is for surfaces to physically interact with each other at the microscopic level. This happens when the surface's pores or micro-roughness create a "composite-like" interphase with the adhesive. As a result, the application of chromic acid, or plasma, for the surface treatment of polyethylene fiber enhances adhesion quality by addressing surface defects and augmenting the interface area between them [62].

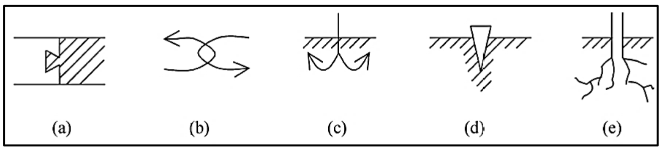


Fig. 4 Conventional models of mechanical connections: **(a)** embedding, **(b)** hooking, **(c)** anchoring, **(d)** nailing, and **(e)** root fastening [5].

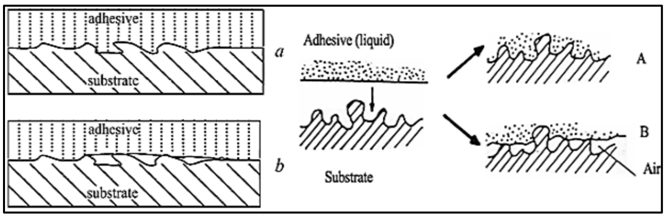


Fig. 5 the pair of cases: (a) sufficient wetness and (b) insufficient wetting [5], [54].

2.1.2. Diffusion theory

Fuyutsuki et al. put forward this theory [63]. According to and based on this theory, adhesive and adherent molecules form strong interactions by diffusing together, as demonstrated in Fig. 6. In addition, each adhesive and substrate should consist of miscible and mutually compatible polymers. Fick's diffusion laws predict that under constant aggregation pressure, both polymeric specimens will diffuse together. The diffusion process is significantly influenced by temperatures, molecule weight, interaction duration, as well as the properties of the polymeric materials. This theory can explain a multitude of phenomena and how they affect the strength and performance of an adhesion bond. In particular, it elucidates the influence of processing environments like temperature and duration on bond performance, the impact of adhesive material types on join strength, and the addition of additives to enhance the strength of certain adhesives. Diffusion theory, nevertheless, presents some constraints. It does not explain the mechanisms involved in joining metallic materials to inorganic substances, including both glass and ceramics [64].

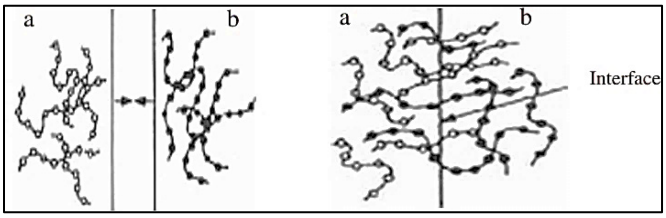


Fig. 6 (a) Adhesive and (b) substrate molecule interdiffusion [54].

2.1.3. Electrostatic/electronics theory

In 1948, Derjaguin et al. proposed the electrostatic theory of adhesion. Later, in 1967, they developed the basis for this theory [65], which depends on the variation in electronegativities between adhesive and substrate material. Based on this theory, consider the adhesive and substrate unit to be a capacitor, and each plate symbolizes the electrical double layer that develops upon contact between two dissimilar materials (Fig. 7) [54], [65]-[66]. When electrons cross the interface, positive and negative charge regions form an electrical double layer.

The electrostatic theory posits that the electrostatic forces at the interfacial contribute to the adhesive-adherent attraction [66]. The adhesive interface allows charge to flow away from the surface when peeled slowly, reducing charge attraction and work required for peeling. Overly rapid peeling may result in insufficient charge dissipation, which in turn increases the adhesive work requirements. This elucidates empirical findings that demonstrate a correlation between bonding strength and peeling speed while also addressing the challenges related to the adsorption theory [67].

Until now, it has not adequately quantified the electrostatic theory's contribution to bonding strength [68]. It is important to note that electrostatic action is present only in bonding systems capable of forming a double electric layer, thus limiting its universal applicability.

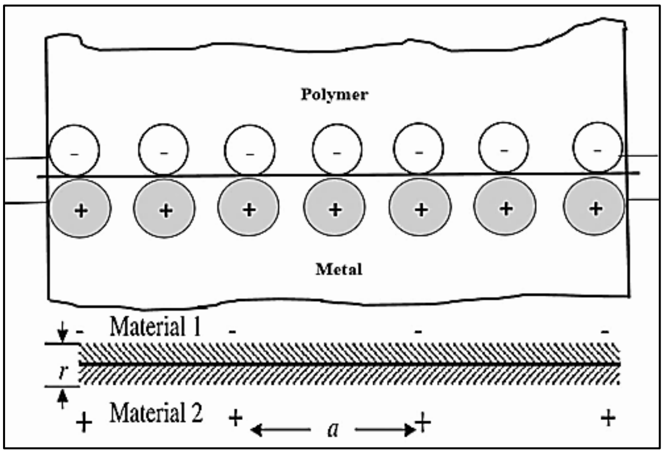


Fig. 7 An electrostatic double layer at polymer-metal interfaces, as well as electron donor and acceptor pairs [54], [66].

2.1.4. Physical absorption theory

This mechanism has received widespread recognition. Schonhorn and Sharpe [69] created the adsorption theory. This theory states that bonds form when adhesive molecules and adherends adsorb or when interatomic forces perform at the adhesive-substrate interface after they touch. It can classify the forces between adhesive and substrate as primary (metallic, ionic, or covalent) or secondary (hydrogen bonds, van der Waals).

This theory includes several models, for instance chemical adhesion, wetting, and rheological, which are sometimes considered separate theories. Surface energy serves as the foundation for the theory, which uses wettability as a standard. Better wetting of the adherend surface makes it easier for adherend and adhesive molecules to come into closer contact with each other, which strengthens the bonding force between molecules at the interface. It is crucial to recognise that as the molecular distance across the adherent and adhesive nears a specific threshold, the van der Waals force emerges as the primary influence [70].

Many comprehensive reviews [55], [71], [72] have elucidated significant results pertaining to the wetting and wettability of polymers. Currently, the existing theory of adsorption effectively associates bonding with intermolecular forces, offering a scientific rationale for the bonding mechanism. However, the adsorption theory by itself cannot completely clarify the bonding process because of its intrinsic complexity. It has notable deficiencies: while the adsorption concept primarily attributes bonds to intermolecular interactions, it fails to explain why the interfacial bonding strength sometimes exceeds the adhesive itself. Adsorption theory suggests that the rate of molecular separation should not influence the amount of work needed to overcome intermolecular forces when a bond fails. Further, adsorption theory fails to explain the relationship between bonding strength and strain rate.

2.2. Primary considerations contributing to adhesion

Adhesion is a multifaceted phenomenon that encompasses polymer synthesis, surface chemistry, and additionally experimental and theoretical mechanics [66]. Establishing the causes of interactions reveals a variety of theories in literature, many of which differ significantly. Mechanical anchoring or press-stud theory describes how the adhering sticks to the substrate's holes and gaps. The film-forming agent's molecules stick to each other through diffusion or contact charges, creating reflection forces. The adhesives and the substrates also interact with each other through polar functional groups, hydrogen bridging bonds, or chemical bonds (Fig. 8) [73]. All the mechanisms mentioned above have the potential to influence bond strength and adhesion. Individual adhesion processes can only significantly contribute when they meet the criteria.

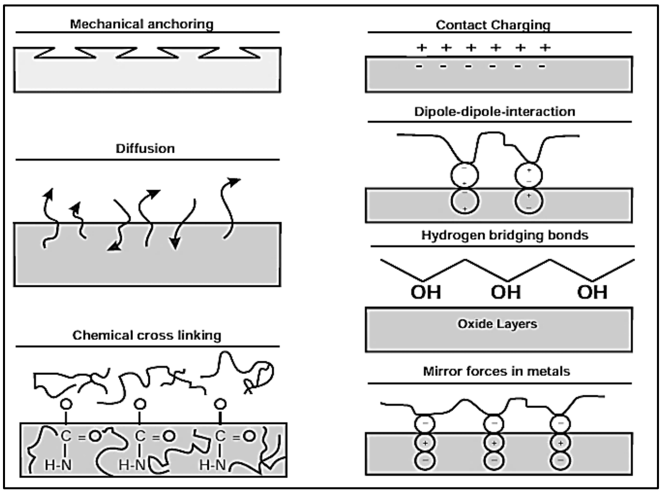


Fig. 8 Chemical and physical substrate adhesion factors [73].

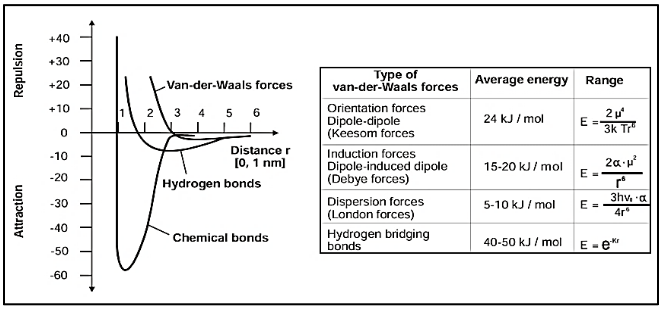


Fig. 9 Graphs showing values of the potential energies of hydrogen bonds and van der Waals forces as contributors to adhesion [73].

The interactions described by the phrase van der Waals forces require a distinct classification. Regardless of the substrate's type and physical characteristics, they are often the primary sources of adhesion. Figure 9 illustrates the potential energy curves and values associated with hydrogen bonds and van der Waals forces, both of which participate in adhesion. Additionally, they comprise directional forces (dipole-dipole interactions), induction forces (dipole/induced dipole interactions), and dispersion forces. Provided there is an adequate chemical structure and substrate, efficient hydrogen bonding interactions may occur [73].

3. Designing and failure of ABJs

The efficiency, overall performance, and bonds strength are significantly dependent on the quality of the fabrication process applied in ABJs. Selecting a suitable adhesive for specific substrate materials, implementing adequate preparation and application method, and implementing specific strength augmentation strategies can all lead to a superior bonding quality. By evaluating the interior morphology and integrity of bonded structures through defect detection, it can prevent initial damage during service [74].

3.1. Adhesive joint configurations

Joints provide one of the most complex challenges in the structure's design, particularly in composites, since they produce discontinuities in the structure's geometry and material characteristics, as well as large local stress concentrations. According to Adams and Wake [75], designers have access to a wide range of joints. Chamis and Murray [76] propose a sequence of steps for the initial design of composite adhesive joints, such as single, double, steplap, and scarf, suitable for both hot and wet service conditions under static and cycle loads. An ideal joint should subject the adhesive to shear forces and maximize the load-bearing area. These are two fundamental principles for design engineering. However, this may not be universally achievable for all types of joints, such as a T joint. The discussion focuses on the general classification of joint configurations into joints displayed in Fig. 10.

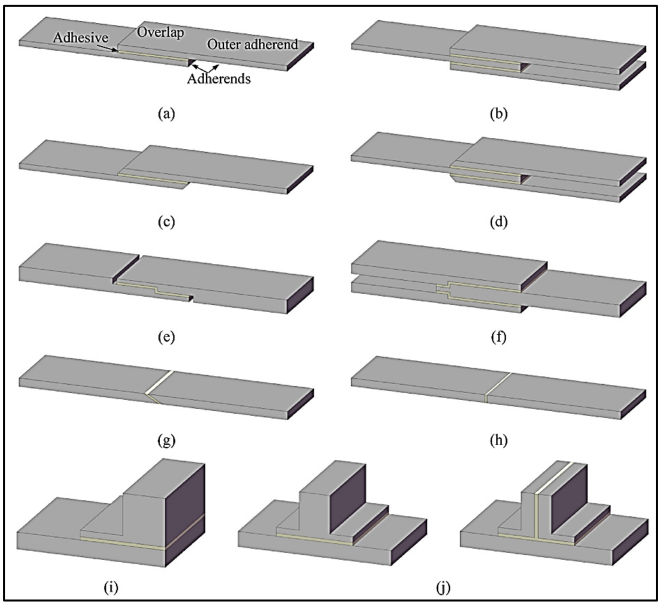


Fig. 10 (a) single lap joint, (b) double lap joint, (c) tapered single lap joint, (d) tapered double lap joint, (e) stepped single lap joint, (f) stepped double lap joint, (g) scarf joint, (h) butt joint, (i) L-joint, and (j) T-joint. [5]

3.1.1. Lap joint

Commonly used in practical applications, lap joints stand out for being structurally simple and straightforward to construct, as well as for their ease of implementation. The lap joint connects adherents into a single entity, allowing the transfer of mechanical loads between them. The two most prevalent forms of joint configurations are single and double laps as shown in Fig. 10 (a) to (d). The industry extensively uses the single-lap joint (SLJ) [50]. Due to their simplicity of manufacture, inspection, and maintenance [77], SLJs are one of the most commonly used joints in aircraft. SLJs are the focus of most research on Non-Destructive Test (NDT) and Structural Health Monitoring (SHM) of adhesively bonded structures. However, other types of joints can easily apply the techniques and processes developed for SLJ [74].

Despite their simple structural design, SLJs indicate both shear and peel stress as a result of the bending deformation that occurred because of their non-uniform path of loading. Hence, manufacturers often select a double lap joint because it enables a consistent distribution of load within the adhesive, thereby mitigating the drawbacks associated with SLJs. Nevertheless, the double lap joint, with its three adherents, not only adds weightiness, but also complicates the fabrication process and increases costs compared to SLJs. This makes it less common in joint constructions where weight reduction is a primary consideration.

3.1.2. Stepped lap joint

Multiple configurations of the stepped double lap and stepped-SLJs are demonstrated in Fig. 10 (e) to (f). The ability of stepped lap joints to mitigate the effects of bending moments caused by eccentric loading motivates their introduction. A three-step lap joint (TSLJ) has considerably higher bending and fatigue strengths than (SLJ). Akpinar [78] conducted an evaluation of the mechanical properties of SLJs, single stepped lap, and TSLJ, all possessing identical bonding areas. The findings indicated that TSLJs exhibited the lowest stress concentration. Durmus and Akpinar [79] investigated how a step's length affects the failure load in a TSLJ under tensile conditions. The failure load may grow substantially when the first and middle step lengths are comparable, as they demonstrated. Nonetheless, this type of joint typically uses composites as the adherend. Ichikawa [80] conducted a study, using experimental and 3-D finite element analysis (FEA), to investigate the performance of ABJs, a stepped-lap joint from steel, in a static tensile load. The study showed that decreasing the thickness of the adhesive, increasing its Young's modulus, and adding additional steps all led to decreased maximum principal stress values at the ends of the overlap region [81].

3.1.3. Scarf joint

The manufacturing process of the scarf joint, as illustrated in Fig. 10 (g), includes performing the bonding portion between the two joints in an inclined plane. The requirement to precisely control the dimension of the oblique adhesive layer and the inclined surface complicates the fabrication process, while the joint formation reduces stress concentration. Adkins and Pipes [82] investigated the mechanical behavior of scarf adhesive joints used in composite materials. They discovered that small angles are extremely sensitive to stiffness mismatches and adherent tip bluntness, resulting in significant stress concentrations. In accordance with Kanani et al. [83], the scarf joint outperforms other designs, and increasing the overlap length has a significant impact on some joints. Furthermore, this configuration design allows for a more uniform distribution of bearing damage, as the adherent tapers at the overlap edge portion. In addition, this configuration design reduces the bending moment by distributing less stress along the joint path.

The angle of the scarf (θ) is a crucial consideration for scarf joints, affecting both structural performance and the mechanisms of failure. When θ is high, adhesive failure typically occurs, whereas with a lower θ, matrix cracking and delamination are more common [84]. Using photoelasticity and FEM, Nakagawa and Sawa [85] investigated scarf joints. The study concludes that an optimum scarf angle exists under a static tensile load; the stress singularity disappears, and the stresses distributions evolve into uniform close to the interface boundary, indicating that the scarf angle is optimal. Nonetheless, the optimum scarf angle does not exist under thermal loads.

3.1.4. Butt joint

The butt joint is the simplest to fabricate. Nevertheless, it is unable to withstand bending stress due to the separation of the adhesive. Fig. 10(h) represents designs that can improve the ABJ's strength in the case of thick adherends. These modifications reduce the adhesive cleavage stress. Tongue-and-groove joint forms exhibit notable effectiveness due to their function as reservoirs for adhesive materials and their self-aligning properties [50]. A butt joint lacks an axial overlap part, resulting in a relatively small load-bearing area and generally poor bonding strength. Furthermore, these joints are inappropriate for environments with complex loads, as they are sensitive to loads that are orthogonal to the adherends' binding surfaces.

3.1.5. T-Joint

In T joints Fig. 10(j), the orientation of two adherends is perpendicular (angle = 90°). Nonetheless, this type of joint also includes components oriented differently from angle 90°. Loading might occur in the plate's plane (N) or transversely (T), as shown in Fig. 11. T-joints are greater in analytical complexity compared to lap joints and other joint types, and there are currently no established analytical methods for design determinations. When necessary, this design can slightly increase the load-bearing ability of ABJs, leading to increased use. Furthermore, the primary point of the recommended procedures is to minimize peel loads whereas maximizing shear loads. Da Silva and Adams [86] empirically showed a stiff foundation base reduces the peel load in the adhesive while significantly increasing the failure load compared to an elastic foundation base. Standard T joints determine failure by yielding the base plate, as an increase in its thickness typically results in a 10x increase in the failure load. When designing for a certain load, T-joint manufacturers must consider substrate behavior, particularly yield.

Apalak [87], [88] investigated the geometrically non-linear design of T-joints as well as achieved similar outcomes. Adhesion areas at the free adhesive-sheet interface also exhibit concentrations of stress. Additionally, they found that increasing support length greatly reduces peak ABJ stresses. The study provides frameworks for design guidelines that consider the fillet, geometric parameters, and length support. For marine applications, Marcadon et al. [89] found that the overlap dimensions and T plywood-base distance affect bonded T-joint tearing strength. The fatigue lifespan of adhesive T-joints has two stages: the initiation stage, which lasts roughly a third of the fatigue lifetime, and the propagation stage, which lasts till failure.

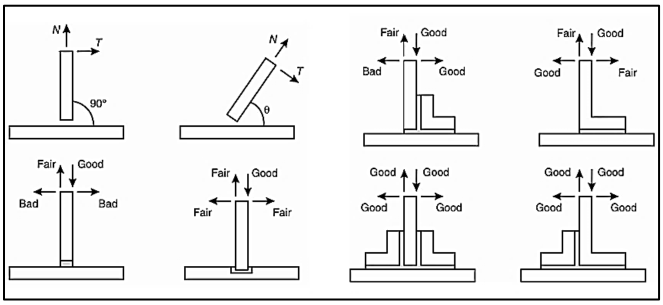


Fig. 11 T-Joints [88].

3.1.6. L-Joint (Corner)

L-joints are like T joints, modified according to Adams et al. [88]. Figure 12 illustrates common ways for reducing adhesive peeling stress. In 1993, Apalak and Davies [90] conducted a linear finite element analysis (FEA) of several corner joints and developed design recommendations based on static stiffness and stress analysis. The primary factor influencing stiffness and stress is the transverse load (T) in Fig. 12. Increasing the length of support and reinforcements, as well as thickness, improves joint strength and reduces peak stress on the adhesive. Feih and Shercliff [91] analyzed a single L joint under a tensile force. Subcritical degradation develops in the composite; however, the adhesive peel layers are a particularly crucial component in the case of a joint failure. Modifying the form of the fillet may boost joint strength by up to 100%, according to experimental results.

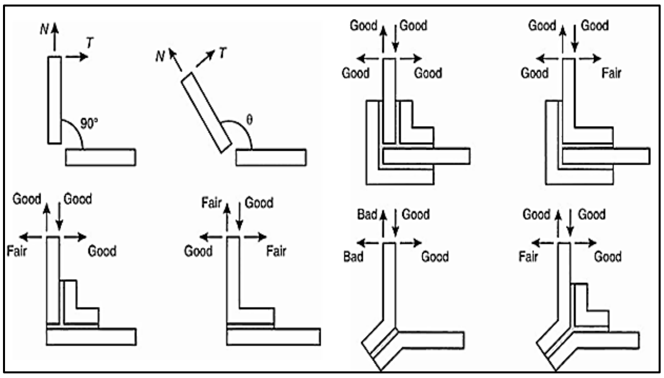


Fig. 12 L-Joints [88].

3.2. Adhesive joint characteristics and failures mod

In general, it is essential to study the properties of materials to evaluate their performance, life cycle, and predict failure. In particular, this section will focus on the properties of the adhesive bond and its types of failure modes under different loading conditions.

3.2.1. Characteristics of ABJs

Table 2 analyzes the key features of ABJs, specifically lap joints. Furthermore, it lists a variety of joint strength percentages and bonding strengths. The joint strength percentage (R) represents the ratio of the bonded joint strength to the adherend strength. The most commonly used types are single/double-lap structures. Production commonly uses sandwich structures, composite materials, and aircraft examples for fuselage constructions, wings, tails, and other joining components [22], [92]. The edge of a single-lap joint tends to peel stress during bending [93]. Consequently, designers are gradually adopting functionally graded adhesives based on their unique characteristics. The preparation involves regulating the ratios of mixing across multiple adhesives, a process known as functional grading [1].

In the butt joint, the adhesive layer thickness significantly influences its performance [98]. In the scarf joint, the scarf bond angle exerts an even more significant influence [99]. The key factors influencing the stepped joint, inserting type, and waveform structure are the step number, access length, and bending degree [101].

Machado et al. [103] employed a mixture adhesive (two brittle and three ductile adhesives) for establishing joints, which had more durable characteristics than adhesive alone. The joints' mechanical properties moulded with functional grading adhesives surpassed those of joints formed with an alone adhesive. Furthermore, increasing strength enhances joint toughness [104]. Various joint lap adhesive configurations exert distinct effects.

Table 2. Characteristics of ABJs, ratios joint strength R (%), and joint bonding strength σ (MPa).

ABJs	characteristics	R	σ	Ref.
Single lap	Basic structure, economical, simple to manufacture, and concentrate stress at the edges.	4	19.2	[93-94]
Double lap	Basic structure, economical, simple to manufacture, and concentrate stress at the edges.	5.3	21.149	[95-96]
Butt	Basic structure, no overlap and limited bonding area.	5.3	69.06	[97-98]
Scarf	Strong bonding and middle cost.	1.8	7.37	[99-100]
Stepped lap	Complex manufacturing progression, yet it has strong loading capabilities.	1.2	11.59	[101-102]

Afterwards, during the analysis, it is crucial to evaluate and assess the application criteria, material properties, and pertinent process variables in order to create joints with the appropriate configuration. It improves the durability of joints, boosts manufacturing efficiency, and effectively manages costs.

3.2.2. Failure modes for ABJs

Failure occurs when an adhesive joint's strength is inadequate to endure external loads. There are several types of failures depending on where the damage occurs. It is critical to investigate the source of failure in order to prevent bonding failure. Some instances include adhesive, cohesive, debonding/adhesive, and mixed failure, as illustrated in Fig. 13(a) to (d). Different failure modes are typically associated with the adherend material, the adhesive, the congruence of the substrate and adhesive, and the modes of load implementation [105].

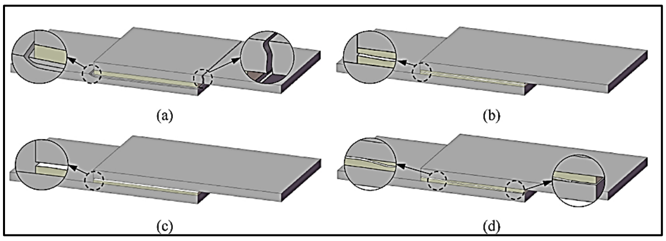


Fig. 13 The failure modes of joints involving adhesion and adhesives. (a) Substrate failure (b) cohesive failure (c) debonding or adhesive failure (d) mixed failure [5].

Cohesive failure is defined as the separation within the adhesive layer. A thin-layer cohesive failure occurs when there is a separation close to the substrate on one side or edge. The crack typically propagates from each overlap end toward the center. The investigation of cohesive failure is a crucial component of the joint fracture mechanics' approach [5].

Adhesive failure refers to the separation that takes place at the interface overlap amongst the adhesive and the substrate, typically manifesting as a brittle failure mode. Therefore, the adhesive may not be substrate-compatible, compromising the interface binding. This implies that the use of adhesives' mechanical properties is never optimal [106].

A mixed failure is a combination of multiple failure mechanisms, including cohesive failure, which occur during the fracture initiation stage and then progresses to adherent material delamination during crack propagation. This is because the bonding region's stress status varies throughout the loading and failure process.

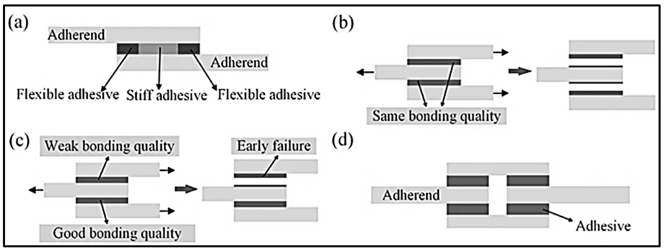


Fig. 14 Examples of joint failure modes: (a) SLJ-mixed adhesive layer; (b) a double-lap joint - same mass on both sides; (c) a double-lap joint-different masses on both sides; and (d) another double-lap structure [92].

This results in an equal distribution of stress, which prevents delamination failure as shown in Fig. 14 (a) [107]. Wei et al. [108] investigated stresses and failure mechanisms for a dissimilar lap joint on both edges. According to this study, dissimilar double lap joints expose unequal loads and are more likely to crack on the thin edge. To analyze the bond area failure mechanism, Zhao et al. [95] conducted an experimental study on double-lap joints under tensile load. Similar failure types at the adhesive boundary were observed when the adhesive surfaces exhibited similar characteristics, as shown in Fig. 14 (b). The side exhibiting poor adherence is shown first in Fig.14 (c). Consequently, the regular application of adhesives along both edges of a double lap joint is critical for enhancing the strength of the joint. It refined the double lap joint design to find a more suitable configuration, as shown in Fig. 14 (d). While this increases the total characteristic of the joining structure, it does not account for its light weight [109-112].

4. Failure analysis criteria and strength prediction

Due to the complex stress condition and singularity in ABJs, it is generally difficult to predict failure [113]. The challenges associated with adhesives include: (1) varying failure mechanisms among the adhesive and the adherend, as well as the interface between them; (2) the influence of pretreatment, for instance surface preparation, curing, and manufacturing problems (defects, flaws, imperfections, etc.) on the adhesive's performance; and (3) the diversity of material conducts, including elastic, inelastic, ductile, and brittle properties. Under dynamic and cyclic loading, predicting the failure of the adhesive bond joint (ABJ) with composite adherents may become increasingly challenging [114]. Literature identifies two primary criteria for predicting ABJs failure: stress analysis and fracture mechanics analysis [115].

4.1. Stress based analysis (continuum mechanics)

The principles of analysis depend on stress and strain, which predict adhesive failure. In terms of stress, this includes maximum shear τ_{max}, maximum peeling σ_{max}, and the von Mises stress. The strain encompasses the maximum shear strain γ_{max}, maximum peeling strain ε_{max}, and longitudinal strain [116]-[125]. However, empirical results showed that for comparatively thick adhesives, the failure stress decreases as the adhesive thickness increases [126]. Consequently, the design of ABJs often uses a failure criterion based on fracture mechanics as a strength criterion [127]-[128]

4.2. Fracture mechanics-based analysis

Fracture mechanics is based on understanding the types of pre-cracks and defects in the structure. It uses these ideas to figure out how strong ABJs are by looking at the stress intensity factor (SIF) and the energy release rate (G) [129]. SIF serves as an index for the variations in states of stress near the crack tip. Conversely, it determines G by comparing the strain energy release rate (GI) resulting from the applied load with its corresponding critical value (GIC) [115]. For strength prediction, of ABJ's design, it is necessary to determine the SIF or G values in addition to their critical values, like fracture toughness or critical energy release rate. The research indicates that it can determine SIF or G through theoretical analysis, numerical modeling, or experimental assessment, but it needs dedicated experiments to study materials for critical values [130]-[133]. In linear elastic fracture mechanics (LEFM), SIF, a theoretical value, is helpful in determining the failure modes for fragile materials [134].

As a function of load and failure prediction, the literature has investigated in extensive detail aspects of fracture energy release rates [135]-[137]. Furthermore, the mixed-mode fracture criteria [138]-[139] significantly affects the strength of ABJs. Recent studies have utilized the Stress Intensity Factor in fracture mechanics to evaluate the strength of ABJs [140]-[141].

4.3. Analysis methods of ABJs

Both analytical and numerical methods enable one to analyze ABJs. Each of these methods presents features and drawbacks, Analytical methods can assess joints efficiently, easily, accurately, and quickly, but they require specific presumptions for complicated ABJs, which may limit the accuracy of the analysis. Numerical methods can evaluate complex ABJs without requiring any assumptions. The only limitation is the time required for computation. The following sections cover the most recent developments in analytical and numerical methods [9].

4.4. Analytical methods

Analytical techniques assist during the initial design of ABJs, reducing cost-effective testing and analysis duration. Volkersen [142] proposed the first shear lag model for ABJs in 1983, assuming that the adhesive is in shear alone, the adherends are in tensile, and that these stresses are constant along the thickness of the joint. Furthermore, Goland and Reissner [143] took adherent bending into account in addition to shear stress, which results in peel stress in the adhesive layer as in Fig. 15.

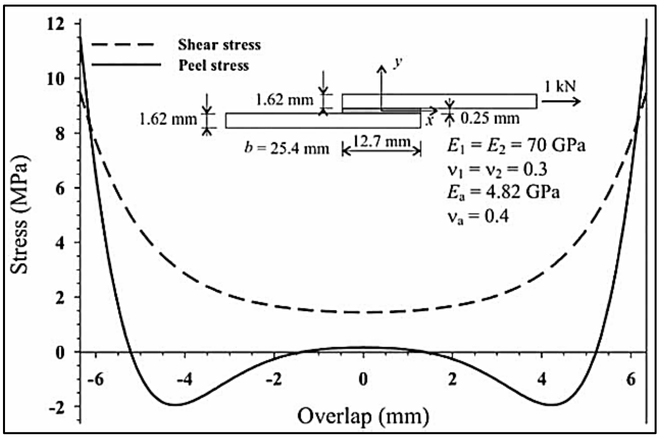


Fig. 15 appears the peel and shear stress distributions according to Goland and Reissner [144].

In the literature, Hart-Smith [145] presented a simple analytical model based on the idealized elastic-plastic behavior of an adhesive layer, focusing on the effect of shear deformation on joint strength. Later studies such as Renton and Vinson [146]-[147] and Srinivas [148] presented models that included the effects of transverse shear deformation in single- and double-layer joints, while studies such as Dattaguru et al. [149] and Pickett and Holaway [150] used nonlinear analysis methods to evaluate the performance of ABJs. Furthermore, the studies addressed advanced analytical methods for evaluating stresses and strengths of ABJs, with emphasis on the effects of bending, shear deformation, and dissimilar materials. These investigations included analytical and numerical methods to improve the prediction of the mechanical behavior of joints, with results confirming the importance of adhesive and material properties [151]-[158]. The results confirmed the importance of including shear deformations, bending, and asymmetrical effects in the prediction of accuracy. The nonlinear models showed superiority in predicting joint strength compared to conventional methods.

Recently, new analytical models have been presented, which will be briefly explored as follows [159]-[165]. Studies have provided accurate analyses of stress distribution in ABJs using analytical and finite element models. The research has focused on the effect of geometric considerations, for instance adhesive thickness, loading and boundary conditions, slope angle, and overlap length, to reduce stresses and enhance ultimate performance.

Analytical models are an effective tool for evaluating stresses in ABJs, as they are highly accurate while minimizing computational effort. Moreover, geometric factors and boundary conditions, such as adhesive thickness, overlap length, and taper angle, play a crucial role in improving performance and reducing interfacial stresses. These models are ideal for advanced engineering applications due to their flexibility, which enables rapid results and simple updating to accommodate changes in dimensions and material properties.

4.5. Numerical methods (FEMs)

Joint geometry, material properties, structural configurations, loading paths, and boundary conditions affect ABJ's mechanical behavior. Due to time and cost limitations, analytical keys for these joints with complex geometry, heterogeneous materials, and nonlinearity of material are challenging to determine. Therefore, numerical models, notably FEA, are preferred for investigating these joints [166-167]. The literature uses numerous methods to provide adhesive joint finite element analysis (FEA). Adams et al. have conducted both linear [168] and nonlinear [169] analyses. Da Silva and Camplho et al. [170] reviewed the numerical modeling of adhesive joints, focusing on damage assessment methods that had seen extensive development at the time. While two-dimensional FEA was initially suitable, the advancement of numerical techniques resulted in the increased adoption of three-dimensional models [171]-[173].

The applications of FEA have been extended to investigate the greater complexity of effects such as impact loading [174], dynamic loading (fatigue) [175], vibration [176], and thermo-mechanical loading [177], with studies demonstrating its efficacy in these cases. FEA is an effective solution for addressing the challenges caused by the complicated geometry and nonlinear nature of ABJs. Recent developments in damage models have enabled a balance between accuracy and efficiency, positioning these models as an optimal solution for applied studies.

4.5.1. Extended finite element method (XFEM)

The extended finite element method (XFEM) is a numerical technique that improves on the classical finite element method (FEM) by extending the solution field to include solutions to equations containing discontinuities. XFEM's development sought to address local feature-related problems such as discontinuities and cracks, which provide difficulties for conventional mesh optimization [134], [178]-[182].

In contrast to classical FEM, XFEM uses a mesh that is independent of the structure's geometry or material interfaces, obviating the necessity for high-density mesh partitioning in regions with concentrated stresses or deformations. In order to locate a fracture in the joint structure without internal details or pre-cracks, a level function was employed. Unlike FEM, XFEM allows element discontinuities by using particular displacement functions and extra degrees of freedom. Since XFEM does not need pre-defined crack paths like virtual crack closure technique (VCCT) and CZM methods do, it is particularly beneficial for simulating damage and crack development [183].

The literature has documented several investigations of ABJs using XFEM [184]-[188], concluding its efficacy in addressing cracks and damage without requiring complicated meshes or pre-existing cracks. Furthermore, it is an advanced option for modeling joints using various materials and different damage conditions.

4.5.2. Cohesive zone model (CZM)

This method accurately describes the entire damage behavior, from the initial stage of cracking to ultimate failure, owing to its precision in predicting failure and addressing stress discontinuity. Cohesion zone modeling (CZM) is a common method for investigating crack initiation and propagation in ABJs, particularly when integrated with finite element analysis (FEA). The experimental determination of the Traction Separation Law (TSL) forms the foundation of this approach, which is based on specialized elements. Nevertheless, CZM faces considerable challenges, including the determination of cohesion parameters, uncertain crack paths, and concerns regarding mesh convergence. The integration of experimental models with specialized elements is essential for the implementation of CZM in FEA [189]-[195]. The stress-displacement separation (TSL) law describes irreversible joint interface conditions like deformation and deterioration. Furthermore, it precisely determines cohesive stress along the interface region [196].

TSL provides significant versatility due to multiple configurations designed for various applications defined by displacement and traction, including Bilinear [197], Trilinear [198], Linear-parabolic [199], Exponential [200], Trapezoidal [201]-[202], and Polynomial [203]. Figure 16 displays some of these formations. However, the TSL is designed such that the total energy per unit area upon complete damage of that component is equivalent to the fracture toughness (Kc), which is established through experimental procedures irrespective of the applied form [205]. This enhances the accuracy of the model.

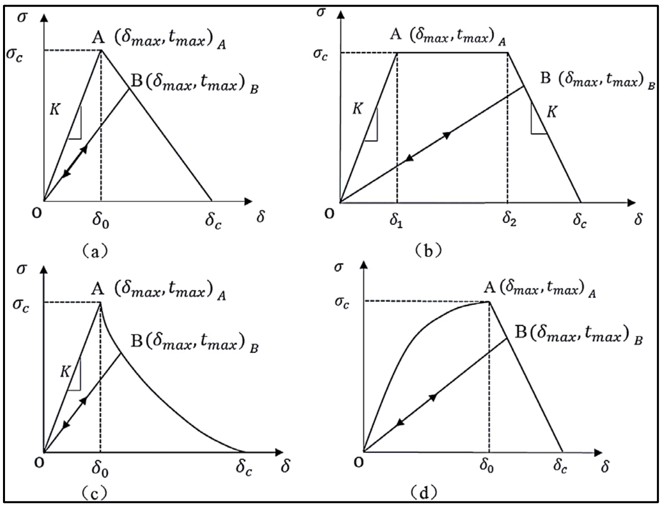
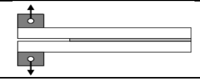
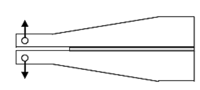
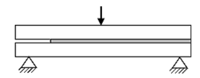
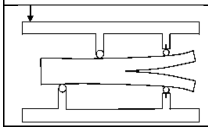
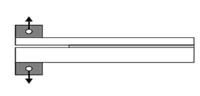
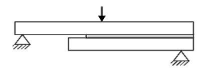
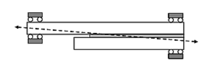
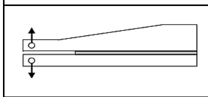


Fig. 16 Irreversible CZM with traction and displacement. Include the following: (a) triangular, (b) trapezoidal, (c) linear-exponential, and (d) exponential-linear [204].

Determining a suitable TSL is crucial for accurately predicting the adhesive's fracture behavior. Research has demonstrated that CZM can effectively model several types of adhesive joints. Bilinear CZM is best suited for brittle joints, exponential CZM for ductile joints, and trapezoidal CZM for both types of joints [206]-[207]. Also, TSL is applied in accessible software (i.e., ABAQUS or ANSYS).

Table 3. Conventional adhesive fracture toughness evaluations.

Structural	Assess Approach	Fracture mod
	Double Cantilever Beam (DCB)	Mod I
	Tapered Double Cantilever Beam (TDCB)	Mod I
	End Notched Flexure (ENF)	Mod II
	Mixed Mode Bending (MMB)	Mixed mod
	Asymmetric Double Cantilever Beam (ADCB)	Mixed mod
	Single Leg Bending (SLB)	Mixed mod
	Crack Lap Shear (CLS)	Mixed mod
	Asymmetric Tapered Double Cantilever Beam (ATDCB)	Mixed mod

Comprehensive CZM modeling includes multidirectional strength and fracture toughness. Under different stress levels, the adhesive joint's effectiveness depends on fracture toughness (Kc) [208]. For comparison, Table 5 lists common literature calibration procedures.

4.5.3. Virtual crack closure technique (VCCT)

VCCT is a extensively recognized and commonly abused numerical method for simulating crack propagation. Irwin [209] first proposed this technique, which states that the energy required to initiate a fracture is equivalent to the energy required for closing it. This technique may be used to analyze the separation of mixed fracture modes and to find strain energy release rates, which are useful for assessing crack propagation. The VCCT technique requires pre-crack and fails to properly represent the nonlinear or peak load portions of the load-displacement curve [210]-[211]. In contrast, the CZM approach does not have this limitation. The literature concludes that nonlinear analysis using VCCT offers a more accurate evaluation of adhesives under critical loading conditions [212]-[213].

5. Conclusions

ABJs have been reviewed in published studies from the past decades to the present, focusing on adhesion theories and factors affecting their performance. Such parameters include geometrical factors (adhesive thickness layers, overlap dimensions, and ABJ components), material properties, manufacturing techniques, and failure mechanisms. All these criteria must be considered while designing bonded joints for excellent structural performance.

Research indicates that there is no comprehensive unified theory describing all adhesive bonds due to the enormous complexity of materials and diverse bonding conditions. Comprehending adhesion requires an in-depth understanding of both surfaces and bulk material properties, in addition to the characteristics of the adhesive. The length scale at which the adhesion phenomenon occurs also plays an important role, with recent focus shifting to the study of adhesion at the nanoscale. The study of adhesion theories is a vital topic for ongoing research and development. Furthermore, it anticipates gradual future developments unless they implement innovative methodologies and experimental strategies.

The type of material to bond, the service conditions, and the application field typically influence the selection of the appropriate bonding technique. However, the effects of jointing techniques on failure behavior and the correlation between the mass adhesive strength and the joint's strength remain uncertain. Selecting the appropriate bonding method for specific applications is of paramount importance. Furthermore, there is no universal correspondence between the strength of the ABJs and engineering parameters like overlap length, adhesive layer thickness, and joint configuration. This is due to potential interference from other factors, such as the properties of the adhesive (ductile or brittle), the loading path and mode, and the condition of the surface substrate material. Therefore, it is essential to take these factors into account when optimizing engineering parameters to achieve maximum joint performance.

Utilizing analytical and numerical methods like XFEM, CZM, and VCCT represents the most effective approach for optimizing geometrical parameters to predict joint strength and failure. The (CZM) serves as an effective tool for simulating progressive damage and crack development in adhesive joints, using stress-displacement rules to identify the phases of separation and damage. Conversely, the (VCCT) focuses on quantifying the energy required to close the crack to determine its growth direction. This method is effective for precise simulations of crack propagation, although it necessitates the existence of a pre-crack. The (XFEM) represents an advancement in finite element analysis, enabling the detection of complicated cracks without requiring mesh reconfiguration, which makes it particularly suitable for the analysis of highly complex engineering structures.

Eventually, continued studies on failure mechanisms are of significant importance, as they contribute to a more comprehensive understanding of the properties of ABJs. Further development of numerical models is essential to address environmental characteristics and enhance overall performance effectively. Advanced computational techniques, particularly those related to data science, indicate an urgent need for further investigation into new modeling and simulation methods for interconnected joints. A future challenge is how to fully leverage the latest understanding of the failure mechanisms of bonded surfaces to improve the performance of the next generation of joints, which calls for further research and development.

Nomenclatures

ABJs	Adhesive Bond Joints
ASICs	Application-Specific Integrated Circuits
FGMs	Functionally Graded Materials
FRP	Fiber Reinforced Polymer
MWTSs	Minimal Wall Thickness Structures
FEM	Finite Element Method
NDT	Non Destructive Test
ABAS	Committee on Adhesive Bonds in Automotive Structures
CZM	Cohesive Zone Models
CFRP	Carbon Fiber Reinforced Polymer
SASs	Soft Adhesive Systems
FCG	Fatigue Crack Growth
PCM	Phase Change material
SLJ	Single Lap Joint
SHM	Structural Health Monitoring
TSLJs	Three Step Lap Joints
DEM	Discrete Element Method
DCB	Double Cantilever Beam
ENF	End Notch Flexure
SIF	Stress Intensity Factor
G_I	Strain Energy Release Rate
LEFM	Linear Elastic Fracture Mechanics
XFEM	Extended Finite Element Method
TSL	Traction Separation Law
VCCT	Virtual Crack Closure Technique

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