

Adhesively bonded joints and their applications

Fehim Findik^{1,2,*}

¹ Metallurgy and Materials Engineering Department, Faculty of Technology, Sakarya Applied Sciences University, Sakarya, Turkey

² Istanbul Aydın University, Mechanical Engineering Department, Engineering Faculty, Florya Halit Aydın Campus, Istanbul, Turkey

*Corresponding author E-mail: name. findik@subu.edu.tr

Received Jul. 28, 2025

Revised Mar. 9, 2026

Accepted Mar. 18, 2026

Online Mar. 31, 2026

Abstract

Adhesively bonded joints offer a superior alternative to traditional mechanical fasteners, providing uniform stress distribution, reduced weight, and the ability to join dissimilar materials. Their versatility makes them indispensable across the aerospace, automotive, and medical industries. However, performance is highly dependent on adhesive selection, surface preparation, and environmental resilience. This study provides a comprehensive critique of failure modes, including interfacial, cohesive, and mixed-mode damage, often triggered by temperature fluctuations or cyclic loading. It further examines standardized testing protocols under ASTM, ISO, SAE, and EN frameworks, such as lap shear and fatigue testing, to ensure structural reliability. A significant portion of the research focuses on sustainability, addressing the challenges of toxicity and recyclability through bio-based materials and reversible bonding. Finally, the study explores emerging innovations like self-healing polymers and AI-assisted selection, which are set to revolutionize the future of adhesive technology. By balancing structural efficiency with environmental considerations, adhesively bonded joints remain a cornerstone of modern engineering.

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Published by ARDA.

Keywords: Adhesive, Bonding, Joints, Failure, Application, Sustainability

1. Introduction

Connecting elements can be divided into two categories: releasable and non-releasable. Releasable joints include screwed joints, while releasable joints include welded joints. A non-releasable joint is also achieved through adhesive bonding. Adhesively bonded joints are joints in which two or more materials are joined using adhesives rather than mechanical fasteners (e.g., bolts, rivets) or welding. These joints rely on the adhesive's ability to transfer loads between the bonded materials (the materials being bonded) through surface adhesion and cohesion [1].

Adhesively bonded joints can be divided into four types: lap joints, butt joints, tee joints, and rhombic joints. Lap joints involve overlapping bonded parts joined along their surfaces. Two bonded parts, usually reinforced and butt-to-end, are joined in a butt joint. In tee joints, one bonded part is joined perpendicularly to the other. Adhesively bonded parts joined at an angle to reduce stress concentrations are included in rhombic joints [2]. Properties such as homogeneous stress distribution, light weight, corrosion resistance, aesthetic appeal, and

vibration damping are among the advantages of adhesively bonded joints. Compared to mechanical fasteners, adhesively bonded joints reduce stress concentrations thanks to their uniform stress distribution. They eliminate the additional weight caused by screws or rivets, making them lightweight. Because adhesives are polymer-based materials, they have high corrosion resistance. Therefore, adhesive joints prevent galvanic corrosion between dissimilar materials. These joints also have an aesthetic advantage because they have smooth surfaces, lacking visible fasteners. Additionally, adhesives are vibration dampers and absorb vibration better than rigid fasteners [3].

Adhesively bonded joints find applications in the electronics, medical, marine, construction, automotive, and aerospace industries. For example, they are used in the bonding of aircraft fuselage panels, wings, and composite structures (e.g., Boeing 787, Airbus A350). They are used in the assembly of automobile body panels and windshields. They are also used in shipbuilding and the bonding of body components; in structural glazing and façade bonding; in the bonding of microchips; and in dental adhesives and prosthetic connections.

Furthermore, adhesive bonding presents challenges such as surface preparation, environmental sensitivity, and inspection difficulties. Before application, the surface must be clean and prepared for bonding. Adhesive bonds are also subject to environmental factors such as humidity and temperature. Furthermore, non-destructive testing (NDT) methods (ultrasonics, thermography) are required to inspect the bonds [3], [4].

In this study, the failure modes such as interfacial failure, intra-adhesive failure, sub-adhesive failure, mixed failure, durability problems, and fatigue damage are reviewed. Also, adhesive selection criteria for adhesives are criticized, including mechanical properties, environmental resistance, curing mechanism, and substrate compatibility. In addition, testing standards of ASTM, ISO, SAE, and EN norms used to evaluate adhesively bonded joints are also investigated. Additionally, sustainability drivers, challenges, and applications of adhesives are also investigated in this study, and future profiles of adhesive bonds are also discussed.

2. Failure modes

A wide variety of failures can occur in adhesively bonded joints. These include interfacial failure, intra-adhesive failure, sub-adhesive failure, mixed failure, durability problems, and fatigue damage. Adhesive failure (interfacial failure) occurs at the adhesive-adhesive interface due to factors such as poor surface preparation, contamination, and poor adhesion. Paint peeling from metal due to inadequate surface treatment is one example.

Cohesive failure (within the adhesive layer) propagates a crack through the adhesive due to overloading, poor bond strength, or deterioration. An example of this failure is the cracking of an epoxy adhesive under shear stress. In adhesive-substrate failure, the bonded material itself fails before the adhesive itself, due to poor adhesion or excessive loading. For example, delamination (separation between layers) occurs in composites. Mixed-mode failure can also occur due to a combination of adhesive, cohesive, and substrate failure. This type of failure is common in real-world applications where multiple stresses act simultaneously.

Furthermore, durability problems can arise due to the surrounding humidity, temperature, and chemical environment. Moisture ingress weakens interatomic bonds. Hydrolysis in epoxies is an example of this. Thermal cycling also causes differential expansion and stress in the heterogeneous composite. Additionally, chemical solvents and acids degrade the adhesives in the composite. Finally, fatigue damage, which is the gradual damage that occurs in composites subjected to cyclic stresses, can occur. Aerospace and automotive applications are among the most common locations where fatigue damage is observed. Before such damage occurs, system components must be periodically inspected using non-destructive testing methods [2].

3. Adhesive selection

For optimal adhesive performance, it's important to consider several factors, including material compatibility, loading conditions, environmental influences, and curing temperature. Because composites combine at least two materials from different groups at the macro level, material compatibility between the polymer, metal, or

ceramic is crucial. Loading conditions such as shear, separation, and stress on the composite material also affect its strength. Additionally, ambient temperature, humidity, and chemical agents also significantly impact performance. Finally, for composites in the cured state, the curing temperature and time, as well as room temperature, are also important factors affecting the mechanical properties of composite materials [3]. Structural adhesive types are listed in Table 1, along with their basic properties, applications, and limitations.

Table 1. Various adhesive types and their properties

Adhesive Type	Key Properties	Applications	Limitations
Epoxies	High strength, chemical resistance, and slow curing	Aerospace, automotive, construction	Brittle, requires surface prep
Acrylics	Fast cure, good impact resistance	Automotive, electronics	Strong odor, moderate temperature resistance
Polyurethanes	Flexible, good peel strength	Windshields, marine	Sensitive to moisture
Cyanoacrylates (Super Glue)	Instant bonding, small gaps	Electronics, medical	Poor impact resistance
Silicones	High temp. resistance, flexible	Gaskets, seals	Low strength

Basic selection criteria for adhesives include mechanical properties, environmental resistance, curing mechanism, and substrate compatibility. Mechanical properties include tensile, shear, and peel strength. Of these, tensile strength is important for butt joints. For lap joints, shear strength is more critical. Peel strength is essential for flexible surfaces [1]. The second fundamental adhesive selection criterion is environmental resistance. Epoxies and silicones used in composites have temperature ranges as follows: epoxies: -60°C to 200°C ; silicones: -100°C to 300°C . Epoxies are resistant to oils and fuels. Acrylics, on the other hand, are degraded in solvents [3].

The third fundamental selection criterion is the adhesive's cure. Curing occurs either at room temperature, with applied heat, or with UV. Room-temperature cure is suitable for field repairs, and two-component epoxies are an example. Heat-cured adhesives offer higher performance, such as aerospace epoxies. UV-cured adhesives also provide a rapid cure for electronic devices [3]. The fourth fundamental selection criterion is substrate compatibility. The compatibility of metals such as steel and aluminum with epoxy and acrylic is important. Similarly, the compatibility of composites such as GFRP and CFRP with polyurethane and epoxy significantly impacts performance. Furthermore, the compatibility of polymers such as PVC and ABS with cyanoacrylates and structural acrylics also affects performance and mechanical properties [4].

4. Failure prevention

Surface treatments, adhesive types, joint design optimization, and environmental protection are important in the joining of composites. Surface treatments such as plasma treatment and chemical primers can be applied as mitigation strategies to prevent wear. Hardened epoxies are used in adhesive modifications for impact resistance. Joint design should also be optimized to prevent damage and improve performance. Increasing the lap length in lap joints and using interlocking joints instead of butt joints are among these optimization measures. Sealants and moisture barriers are also important for the environmental protection of composites [5], [6], [7].

5. Applications

Adhesively bonded joints are widely used in aerospace and automotive applications due to their light weight, high strength, and fatigue resistance. Below are real-world case studies illustrating their use, challenges, and solutions.

5.1. Aerospace industry

Composite bonding in Boeing, Airbus, and SpaceX aerospace systems can be taken as an example. Carbon fiber-reinforced polymer (CFRP) composites were used in the composite fuselage joints of the Boeing 787 Dreamliner aircraft. Epoxy-based film adhesive (Cytec FM 300) was used in these composite joints. However, these joints present certain challenges. For example, they may face problems with long-term durability under cyclic loads and delamination due to moisture ingress. Solutions include surface treatments such as plasma treatment, selecting the correct adhesive, and non-destructive testing, such as ultrasonic testing, to detect defects such as voids. As a result, bonded joints are 20% lighter than riveted aluminum structures and have better fatigue life than traditional fasteners. Cracks were found in the bonded wing joints of a Boeing aircraft five years after production. This was determined to be due to microcracks in the adhesive resulting from cyclic thermal stresses. A modified adhesive formula with silicone hardeners was developed to address this damage [8].

The second example relates to an Airbus aircraft. Hybrid metal-composite bonding was applied to aluminum ribs on the Airbus A350 XWB using Henkel Loctite EA 9394 (2-component epoxy) adhesive to bond CFRP wings. Galvanic corrosion and uniform bond thickness between the aluminum and carbon fiber were also challenges, but these were overcome. The solution was to use fiberglass insulation and conductive liners to address the corrosion problem. Also, an automated application was used for robotic adhesive application for consistency. As a result, the adhesive bonded joints supply 30% faster assembly compared to mechanical fastening and no reported corrosion failures after 10 years of service [8].

The third example is the cryogenic fuel tank bonding application on the SpaceX Falcon 9 spacecraft. This application uses 3M Scotch-Weld EPX epoxy-based adhesive for aluminum-lithium fuel tank bonding at cryogenic temperatures (-253°C). There are some challenges here, such as maintaining bond integrity under extreme thermal contraction and brittle fracture problems. Flexible epoxy can be used as a solution, or stresses can be optimized using finite element analysis. As a result, over 100 thermal cycles have been overcome without failure [9].

5.2. Automotive industry

The first example is the structural battery pack bonding application on the Tesla Model 3. SikaPower®-498, a high-impact polyurethane-based adhesive, was used to bond aluminum battery cases to CFRP panels. This application presents several challenges, including high impact resistance for crash safety and fire resistance. To overcome these challenges, intumescent adhesives were used to close gaps that expand under heat, and their crashworthiness was verified against relevant crash test standards (FMVSS 301). As a result, adhesive bonding of the composites in these cars resulted in a 15% weight savings and a 5-star NHTSA crash test rating [10].

The second example is the carbon fiber passenger cell bonding application in the BMW i3. In this application, the different materials (CFRP + aluminum + thermoplastics) were joined using epoxy-based Dow Betamate™ 1496 adhesive. The different materials also have different coefficients of thermal expansion, which creates a bonding challenge. High-volume production curing requirements also present challenges in this application. However, these challenges have been overcome by rapid curing using conductive heating and rapid primerless adhesive applications. As a result, assembly time for this adhesive-based joint has been reduced by 50% compared to riveting [11].

The third example is the aluminum body panel bonding application on the Ford F-150. In this application, the aluminum hood and doors were bonded using acrylic-based Lord 7542 adhesive. The challenges in this application were vibration resistance in off-road conditions and paint bake cycle compatibility (180°C). To address these challenges, pre-applied adhesive tapes were used and simulated for a 10-year service life using accelerated weathering tests. As a result, adhesively bonded joints are 40% lighter than steel and require no warranty coverage for adhesive failures [11].

In summary, it can be said that material compatibility is critical in adhesive applications, environmental durability must be verified, automation plays an important role in quality production, and the use of non-

destructive testing methods, such as ultrasonic, for quality control is important in detecting hidden voids in adhesive applications on aircraft.

6. Testing standards

Testing standards ensure the reliability, durability, and performance of adhesively bonded joints in industries such as aerospace, automotive, and construction. Tables 2-8 provide a breakdown of the key ASTM, ISO, SAE, and EN standards used to evaluate adhesively bonded joints [4], [7].

Table 2. Various ASTM standards, test methods, and application areas

Standard	Test Method	Application
ASTM D1002	Apparent Shear Strength of Single-Lap Joints	Measures the shear strength of metal-to-metal bonds.
ASTM D3165	Strength Properties of Adhesives in Shear by Tension Loading	Evaluates the shear strength of plastics and composites.
ASTM D3166	Fatigue Properties of Adhesives in Shear by Tension Loading	Determines fatigue life under cyclic loads.
ASTM D3167	Floating Roller Peel Resistance of Adhesives	Tests the peel strength of flexible bonds (e.g., automotive panels).
ASTM D3433	Fracture Strength in Cleavage of Adhesive Bonds	Measures resistance to crack propagation (mode I fracture).

Table 3. Various ASTM standards for environmental testing, test methods, and application areas

Standard	Test Method	Application
ASTM D1183	Resistance to Cyclic Laboratory Aging Conditions	Simulates long-term environmental exposure.
ASTM D3762	Adhesive Bond Strength via Wedge Test	Evaluates bond durability under humid conditions (common in aerospace).
ASTM D896	Resistance of Adhesive Bonds to Chemical Reagents	Tests chemical resistance (e.g., fuels, solvents).

Table 4. Various ASTM standards for surface preparation, test methods, and application areas

Standard	Test Method	Application
ASTM D2093	Preparation of Surfaces for Adhesive Bonding	Standardizes cleaning and treatment methods.
ASTM D1337	Storage Life of Adhesives	Determines shelf life under specified conditions.

Table 5. Various ISO standards for mechanical testing, test methods, and application areas

Standard	Test Method	Application
ISO 4587	Tensile Lap-Shear Strength of Rigid-to-Rigid Bonds	Similar to ASTM D1002 but used globally.
ISO 8510-1	Peel Test for Flexible-to-Rigid Bonds	Measures peel resistance (e.g., tapes, films).
ISO 11343	Impact Resistance via Wedge Impact Method	Evaluates crash performance (automotive).

Table 6. Various ISO standards for environmental testing, test methods, and application areas

Standard	Test Method	Application
ISO 9142	Accelerated Aging for Structural Adhesives	Simulates long-term weathering.
ISO 10365	Visual Inspection of Bond Failures	Classifies failure modes (cohesive, adhesive, mixed).

Table 7. Various EN standards for aerospace, test methods, and application areas

Standard	Test Method	Application
EN 2243-1	Peel Testing for Aerospace Adhesives	Airbus/Boeing-approved peel tests.
EN 6065	Wedge Test for Durability	Mandatory for aircraft composite bonding.

Table 8. Various SAE standards for the automotive industry, test methods, and application areas

Standard	Test Method	Application
SAE J1523	Motor Vehicle Adhesive Test Standards	General automotive adhesive testing.
SAE J2665	Adhesive Joint Durability in Corrosive Environments	Validates bonds in salty/humid conditions.
SAE J2749	Structural Adhesive Performance	Crash-resistant adhesive testing.

There are also EN and NADCAP standards. EN is known as "European Norms," and NADCAP stands for "Aerospace Accreditation." For example, EN 1465 is similar to ISO 4587, which is used for tensile-shear strength testing. NADCAP AC7101 is the aerospace adhesive bonding inspection standard and is a required standard for suppliers such as Airbus, Boeing, etc.

Furthermore, common tests used for adhesively bonded composites include the lap shear test, wedge test, peel test, and fatigue test. The lap shear test utilizes ASTM D1002 or ISO 4587 standards. Two metal/composite strips bonded in a single-lap configuration and pulled under tension are tested, and the shear strength is calculated in MPa. The wedge test utilizes ASTM D3762 or EN 6065 standards. In this test, a wedge is forced into a bonded joint and then exposed to moisture. This test measures crack growth rate and environmental resistance. The peel test, applied to composite joints, involves peeling a flexible adhesive at 90° or 180° angles, and the peel strength is calculated in N/mm. Finally, fatigue testing is performed on composite materials manufactured with adhesives according to ASTM D3166. In fatigue testing, cyclic loading is applied until failure, and fatigue life is determined.

7. Sustainability

Adhesively bonded joints contribute to sustainability by enabling lightweight designs, reducing energy consumption, and minimizing waste compared to traditional mechanical fastening or welding methods. However, their environmental impact depends on the adhesive formulation, manufacturing processes, and end-of-life recyclability. Below is a breakdown of sustainability drivers, challenges, and applications.

7.1. Environmental

The environmental benefits of adhesively bonded joints include light weight, material efficiency, reduced emissions, and prevented corrosion. Lightweight and fuel efficiency are crucial in the aerospace industry [12]. Adhesives reduce weight and increase fuel efficiency by eliminating the use of rivets and bolts. For example, the Boeing 787's bonded composite structure provides 20% fuel savings compared to aluminum. Similarly, in electric vehicle batteries, structural adhesives replace heavy metal fasteners, extending battery range.

Adhesively bonding composites prevents material weakening because there are no holes, unlike rivets, allowing for the bonding of lightweight materials such as CFRP and aluminum to thin/composite materials. Reduced production emissions are achieved through lower energy consumption and fewer processing steps. This is because the curing of adhesives generally requires less energy than welding. Adhesively bonded joints eliminate the need for machining, grinding, and finishing processes. Adhesive's seal dissimilar metals, preventing corrosion problems when joining aluminum and CFRP composites on the Airbus A350, for example. This results in longer-lasting connections because replacement frequency is reduced.

7.2. Challenges

Adhesive bonding of composite materials presents several challenges to sustainability, including toxicity, recycling, and durability [13]. These challenges can be addressed as follows:

First, there is the issue of adhesive composition and toxicity. Petroleum-based epoxies/acrylics are derived from non-renewable resources and are toxic. Some adhesives, including those containing volatile organic compounds, emit harmful emissions during curing.

Secondly, there are recycling and end-of-life issues. Thermosetting adhesives like epoxy and polyurethane are not recyclable due to their strong cross-linking. Adhesively bonded structures like CFRP are also difficult to recycle.

Thirdly, there is the conflict between durability and disassembly. Repairs made with strong adhesives hinder recycling. Furthermore, EU regulations (ELV Directive) mandate recyclability for adhesively bonded joints used in the automotive industry. However, this poses a significant sustainability challenge, particularly when thermoset-based adhesives are used, as recycling is virtually impossible.

7.3. Solutions

Recyclable, separable, and low-water-based adhesives can be used as solutions to sustainability challenges, and design strategies can be developed for sustainability [13]. Bio-based and recyclable adhesives are compared in Table 9, with respect to their types, sources of origin, and disadvantages.

Table 9. Bio-based & recyclable adhesives

Type	Source	Applications	Limitations
Soy-Based Epoxies	Soybean oil	Automotive interiors	Lower strength
Lignin Adhesives	Wood pulp	Packaging, construction	Brittleness
PLA (Polylactic Acid) Adhesives	Corn starch	Disposable products	Low heat resistance

Separable adhesives used as solutions exhibit thermally reversible behavior. This means that heat weakens the bond for removal, which is why, for example, a BMW i3 battery can be recycled. Similarly, UV-separable adhesives degrade under UV light and are used in electronics. Low-water-based adhesives are used in the automotive and construction sectors. For example, Henkel Teroson EP 5055, a low-emission epoxy, is used in the automotive industry. SikaTack®-Panel, a solvent-free PU adhesive, is used in the construction industry.

While the methods mentioned above are used to solve sustainability problems, proper design is also important for sustainability. In terms of design, opting for monolithic joints and using relevant selection guidelines when selecting adhesives are important strategies for overcoming these challenges. Monolithic joints and optimized geometries reduce adhesive consumption. Furthermore, using adhesive selection guidelines helps control environmental impacts.

7.4. Applications

Sustainable applications include applications in the aviation, automotive, construction, and electronics industries [14]. In the aerospace industry, bio-epoxy has been used in non-critical structures, such as Boeing

and Airbus aircraft. Research is also underway on enzymatic adhesive degradation for recycling end-of-life aircraft. In the automotive industry, for example, Tesla uses structural PU adhesives with a 30% bio-content in its Model Y. Ford Automotive prefers recyclable acrylic adhesives for aluminum body panels. In the construction sector, bio-adhesives are replacing formaldehyde-based adhesives in cross-laminated timber. Silicone adhesives with a 25-year lifespan are used in adhesive bonds used in solar panels. UV-curable and water-soluble adhesives are also used in consumer electronics applications. For example, Apple used UV-curable adhesives to remove iPhone batteries. Samsung used water-soluble adhesives for screen repairs.

8. Future perspectives

The field of adhesively bonded joints is rapidly evolving, driven by advances in materials science, Industry 4.0 technologies, and sustainability demands. Below is a critical review of emerging trends, breakthrough innovations, and future applications across sectors.

8.1. Innovations

Smart adhesives and nano adhesives can be considered as advanced materials for adhesively bonded joints. Table 10 lists the different types of adhesives, their functionalities, and application areas. For example, a self-healing polymer developed at MIT in 2023 extended the lifespan of adhesive-based space applications by 300% [15].

Table 10. Different types of adhesives, their functionalities, and applications

Type	Functionality	Applications
Self-Healing Adhesives	Microcapsules release healing agents upon crack detection	Aerospace, wind turbine blades
Conductive Adhesives	Embedded nanoparticles (Ag, graphene) for electrical bonding	Flexible electronics, EV batteries
Phase-Change Adhesives	Reversible softening at specific temperatures	Repairable consumer electronics

Nano adhesives can be categorized as carbon nanotube, biological, and gecko-style adhesives. Carbon nanotube (CNT)-enhanced adhesives have increased strength ($\uparrow 40\%$) and thermal conductivity. Biologically inspired adhesives mimic gecko feet (reusable dry adhesive) or mussel proteins (underwater adhesive). For example, NASA's Gecko Gripper, developed in 2024, uses biomimetic adhesives to achieve zero-gravity results [16].

8.2. Industry 4.0

Future work could utilize Industry 4.0, the rapid technological advancement that utilizes artificial intelligence and robotic automation in adhesive selection. In Industry 4.0, the right adhesive can be selected using artificial intelligence and machine learning. Here, AI assists in adhesive selection by recommending formulations that incorporate mechanical loads, environmental conditions, and sustainability goals. Of course, before physical testing, the adhesive's behavior under real-world stresses must be simulated. For example, Siemens' Simcenter has been shown to reduce adhesive prototyping costs by 50% through virtual testing.

Furthermore, robotic automation, such as 3D printing, can be used for adhesive bonding. Precision additive manufacturing for complex geometries is used in the manufacture of various aircraft parts, such as the Airbus. Furthermore, embedded sensors measure voltage with microfiber optics, temperature with RFID tags, and corrosion with pH-sensitive dyes. For example, in 2025, BMW's Smart Factory uses AI-powered robotic dispensers to apply adhesives with 0.1 mm precision [15].

8.3. Circular economy

Sustainability and a circular economy could also be potential future developments. Here, we can discuss closed-loop adhesive systems and carbon-negative adhesives. Table 11 provides information on the mechanisms and application areas of closed-loop adhesive systems. For example, fully recyclable PU adhesives were used in

Adidas sneakers in 2025. In carbon-negative adhesive systems, CO₂-based polyurethanes capture emissions as raw materials. Algae-derived epoxies, on the other hand, reduce petroleum dependency. The EU's "green deal" mandates 100% recyclable adhesives in the automotive industry by 2030 [17].

Table 11. Closed-loop adhesive systems

Innovation	Mechanism	Impact
Enzymatic Debonding	Bio-enzymes break adhesives at end-of-life	Enables CFRP recycling
Dynamic Covalent Bonds	Heat/light-triggered reversible adhesion	Repairable wind turbine blades

8.4. Industry applications

Emerging industrial applications include space exploration, wearable technology, and energy conversion. For lunar habitat construction in space exploration, regolith-binding adhesives could be used for in-situ resource utilization. Space-grade adhesives are also being tested for orbital debris repair. Biodegradable surgical adhesives that can replace sutures are also important in medical wearable technologies. For example, Gecko Biomedical's light-activated adhesive is a testament to this. Flexible conductive adhesives that can be used as skin patches are also highly practical applications. Adhesives used for hydrogen storage and new solar cells are also crucial in energy conversion. Cryogenic adhesives (-253°C) are used for H₂ storage in hydrogen tanks. Similarly, UV-curable adhesives in perovskite solar cells enable flexible PV panels. Also, bonded composite patch repair is a developing technology that has been used in the aerospace industry for the purpose of improving the mechanical properties of structures [18], [19], [20], [21]. The mechanical properties can be monitored by experimental as well as FEM modeling (Table 12, Figure 1).

Table 12. Mechanical properties of aluminum 2024-T3, FM300 adhesive, and graphite epoxy/Hercules AS4/5-3501-6 [20]

Material	Aluminum 2024-T3	FM300 adhesive	Graphite epoxy/Hercules AS4/3501-6
Elastic modulus, E (MPa)	72400	2756	81800
Poisson's ratio, ν	0.33	0.3	0.31

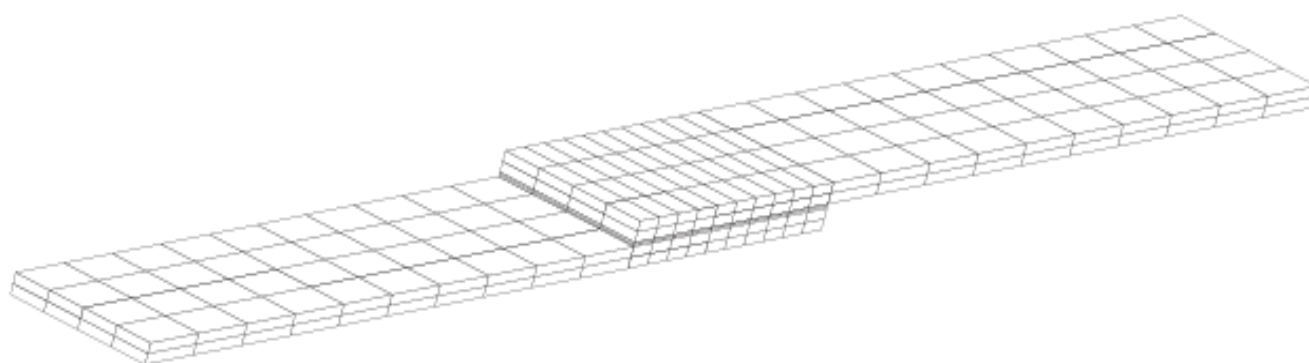


Figure 1. Finite element model of an adhesive-bonded single-lap joint [21]

8.5. Roadblocks

Some challenges and obstacles may be encountered in the future. For example, future challenges may include technical hurdles, a lack of standardization, and high cost.

Among these technical hurdles may be the need for high-speed curing (<10 seconds) for mass production in the automotive industry. Similarly, for Mars-class adhesives, requirements such as extreme environmental stability during thermal cycling and radiation may be considered technical hurdles.

The second obstacle is the lack of standardization. These include the lack of global standards for emerging bio-adhesives and self-healing systems. ASTM/ISO committees are currently working to develop test methods for separable adhesives and standards for biodegradable polymer adhesives.

The third obstacle is the unaffordability of adhesive prices. Bio-adhesives are currently two to three times more expensive than epoxies. Furthermore, limited production capacity for CNT-reinforced adhesives is also a potential obstacle.

8.6. Future timeline

Table 13 provides information on possible developments in adhesives between 2025 and 2040, their impacts, and areas of use.

Table 13. Future timeline between the years of 2025 and 2040

Year	Development	Impact
2025	First commercial self-healing aircraft adhesives (Airbus)	50% fewer inspections
2028	AI-designed adhesives dominate 30% of the automotive market	Custom bonds per vehicle model
2032	CO ₂ -negative adhesives reach price parity	Net-zero manufacturing
2035	Space-rated adhesives used in lunar concrete	Permanent Moon bases
2040	Programmable matter adhesives (morphing bonds)	Adaptive infrastructure

9. Recent studies

Recently, a lot of investigations have been done about the numerical investigations as well as experimental applications. Some of them will be reported here. In numerical studies, nanocomposites [22], CFRP-steel joints [23], modeling and experimental work for CFRP-Aluminum joint [24], hybrid single lap joints [25], CFRP single lap joints [26], and modeling and machine learning [27].

9.1. Modeling works

Within the recent modelling investigations, one study [22] presents a numerical and experimental investigation of the bending behavior of nanocomposite adhesive-bonded joints, specifically aluminum 2024 T3 parts bonded with DP270 adhesive reinforced with graphene nanoparticles. Initially, a finite element model for the double-stranded joint (DSJ) was developed to determine its modal properties, and the results were solved using MATLAB. These results closely matched those obtained from both ANSYS simulations and experimental data.

On the other hand, the creep behavior of CFRP-steel joints was investigated [23] using experimental tests and numerical analysis. Ten characterization tests were conducted to evaluate the thermal stability and viscoelastic creep properties of the reinforcing adhesive. The findings revealed a significant increase in creep rate as the temperature approached the glass transition temperature of the adhesive (63.9 °C). Based on these results, a viscoelastic structural model was developed and applied in the numerical analysis of the creep performance of CFRP-steel joints.

Another study [24] aimed to investigate the impact response and damage tolerance of adhesive-bonded joints (ABJs) using experimental and finite element analysis methods. First, specific impact tests were performed on a specimen with fixed boundary conditions to characterize the mechanical response of ABJs under real service conditions. Second, the impact resistance of rigid and flexible adhesives was compared, and the flexible adhesive was found to be a better choice. Third, the effects of different substrate materials on damage tolerance were investigated. Experimental results showed that CFRP aluminum joints with CFRP plates are a recommended configuration for carrying impact loads.

In addition, another study [25] has been done about the mechanical performance of resistance spot-welded, adhesive-jointed, and hybrid single lap joints, examining the effects of spot weld diameter and the ductile-brittle properties of the adhesive layer. The ABAQUS/Explicit finite element program was used to model three-dimensional adhesive-jointed, resistance spot-welded, and hybrid joints made from advanced high-strength steel (AHSS) DP1000. To optimize joint designs and improve reliability and durability in complex engineering applications, three adhesives (SikaPower 423 L1, Araldite AV138, Araldite 2015), three spot weld diameters, and three bonded material thicknesses were investigated. The results show that the hybrid joint using SikaPower 423 L1 adhesive achieved 14.4 J of energy absorption and demonstrated a 22% improvement compared to the resistance spot-welded (RSW) joint.

Furthermore, finite element simulations [26] of Single Layer Shear (SLS) tests were performed, focusing on the local stress state at fracture initiation. The analysis considered unidirectional and semi-isotropic carbon fiber reinforced plastic (CFRP) adhesives bonded with three adhesives: polyphenylene sulfide (PPS), polyether ether ketone (PEEK), and epoxy. Adhesive thicknesses ranging from 0.1 mm to 0.5 mm were evaluated. The results showed that the optimum thickness to maximize bond strength is between 0.1-0.3 mm. These findings were found to be consistent with experimental trends and support the development of precise design guidelines for polymer-based bonds in structural applications.

Finally, another study [27] evaluates the effects of microstructural features and material properties on structural strength using a combination of finite element modeling (FEM) and regression (GBR) with machine learning (ML). Microstructural features include adhesive thickness, voids within the adhesive, adhesive-adhesive interface voids, void size and volume ratio, and surface roughness. Using FEM, changes in the structural strength and morphology of bonded metal structures depending on different microstructural features and material properties are elucidated. This work provides valuable insights for the development of improved structural bonding methods for adhesive bonding in the automotive and aerospace industries.

9.2. Experimental investigations and applications

Additionally, numerous experimental studies have been completed for the aerospace [28], [29], [30], automotive [31], and other [32], [33] application areas.

Within the current experimental investigations, an aerospace [27] study evaluates the performance of adhesive-bonded junctions (ABJs) of thermoplastic composites in terms of fracture toughness and dynamic-mechanical analysis (DMA) under environmental conditions such as room temperature (RT), low temperature (LT), high temperature (HT), and cyclic hygrothermal (CHT). Furthermore, fracture failure behavior studies using acoustic emission (AE) monitoring, detailed stereo microscopy, and scanning electron microscopy (SEM) provided a comprehensive understanding of the effects of various environmental conditions.

The results show that HT and CHT conditions significantly reduce both mod-I and mod-II fracture toughness compared to RT, while LT conditions increase mod-II toughness, although decreasing mod-I toughness. Under CHT conditions, the combined effects of thermal cycling and humidity lead to a reduced interstitial storage modulus and a lower glass transition temperature (T_g) of the adhesive film. These novel findings highlight the critical role of environmental factors in the design of ABJs for aerospace applications.

Furthermore, other aerospace studies [29] experimentally, numerically, and analytically investigate the effect of joining methods on the strength of composite joints. The single-lap joint shear strengths obtained by joining carbon fiber reinforced epoxy composite parts using mechanical riveting, secondary bonding, co-curing, and co-bonding techniques were compared. Furthermore, the effect of adhesive thicknesses (0.2, 0.4, 0.6, 0.76 mm) on single-lap shear strength was investigated. Moreover, interface damage in the composites was examined using scanning electron microscopy (SEM). The fracture mechanisms corresponding to the bonding methods were also evaluated by examining the fracture surface of the composite samples. Finally, the results were analyzed using Hypermesh, ABAQUS, and ESAComp software.

In addition, a further aerospace study [30], hygrothermal outdoor aging conditions were selected to conduct aging tests (0-28 days) on aluminum alloy-mild steel (AL-MS), (MS-MS), and (AL-AL) single lap joints (SLJ). The microstructure of the fracture surface was examined using high-resolution scanning electron microscopy (HR-SEM). The results show that hygrothermal aging conditions accelerate the displacement reduction for AL-AL joints compared to MS-MS and MS-AL joints. As the hygrothermal aging time increased, the fracture surface of the adhesive joints decreased significantly. HR-SEM analysis revealed that the cracks and morphological changes occurring in the adhesive-joined joints were an effect of hygrothermal aging.

The subsequent application area for automotive [31], another study aims to focus on the design of adhesive-bonded Single Layer Joints (SLJs) under quasi-static compression loading mode, providing relatively high strength and high energy absorption compared to those under tensile loading. To investigate the mechanics of damage progression in SLJs under buckling loading conditions, initially, joints with different bonded material thicknesses and overlap lengths were tested under compression loads.

Subsequently, an advanced 3D finite element model was created using Abaqus/Standard and validated with experimental results, confirming the accuracy of the predicted load-displacement curves. Investigating the initiation and progression of damage in compressed joints provided insights into the relevant failure mechanisms. Increasing the bonded material thickness from 4 mm to 6 mm increased energy absorption by more than 80%, demonstrating a greater effect compared to the overlap length.

In the other experimental study [32], the effects of thermal aging on bonded joints with both similar (Al/Al and CFRP/CFRP) and different (CFRP/Al) materials were experimentally investigated using double cantilever beam (DCB) tests. To predict their long-term performance, aging processes were carried out on adhesive-bonded joints at different temperatures and varying exposure times. The load-displacement response, failure modes, and fracture toughness of the three types of joints investigated were introduced and compared. The results showed that adhesives and bonded joints are affected not only by extreme environments but also by aging time. Among the tested configurations, CFRP/CFRP joints showed the highest adaptability to extreme environments, followed by Al/Al joints, while CFRP/Al joints showed the lowest adaptability. These findings provide useful information about the thermal effects on the permanent properties of adhesive joints for aircraft applications.

The last tentative study [33] utilized plasma modification of both the adhesive and surfaces to improve the interfacial bond between thermoset-based adhesive tape and carbon fiber reinforced thermoplastic polymer (CFRTP) for structural bonding applications. Single-layer shear tests were conducted on AA6061-CFRPPA (carbon fiber reinforced polyphthalamide) adhesive-bonded joints of different materials, demonstrating that plasma treatment alone could increase the shear strength (LSS) by 200% compared to untreated counterparts. An additional plasma treatment applied to the adhesive tape surfaces resulted in a further improvement in LSS (Linear Shear Strength) of up to 315% due to the formation of a denser cross-linked network of covalent bonds.

In summary, some recent studies have investigated adhesive-bonded joints, focusing on numerical modeling and experimental applications in aerospace and automotive contexts. The numerical investigations examined parameters such as adhesive thickness, material composition, temperature effects, and damage tolerance, using finite element methods and machine learning to evaluate joint performance under various conditions. The most recent experimental studies evaluated fracture toughness, environmental aging, and surface modification techniques such as plasma treatment to improve bond strength.

Key findings highlight the significant impact of temperature, hygrothermal aging, and adhesive properties on joint durability and offer specific recommendations for optimizing joint design, material selection, and processing methods to improve structural integrity and energy absorption.

10. Conclusions

The following conclusion can be drawn from the present investigation:

- Advantages of adhesively bonded joints include uniform stress distribution, light weight, corrosion resistance, aesthetic appeal, and vibration damping. Compared to mechanical fasteners, adhesively bonded joints reduce stress concentrations through uniform stress distribution. They increase their lightness by eliminating the additional weight of screws or rivets. Adhesively bonded joints are used in the electronics, medical, marine, construction, automotive, and aerospace industries.

- A wide variety of damage can occur in adhesively bonded joints. These include interface damage, intra-adhesive damage, sub-adhesive damage, composite damage, durability issues, and fatigue damage. Adhesive damage (interfacial damage) occurs at the adhesive-adhesive interface due to factors such as inadequate surface preparation, contamination, and poor adhesion.

- For optimal adhesive performance, it is important to consider several factors, including material compatibility, loading conditions, environmental influences, and curing temperature. Because composites combine at least two materials from different groups at the macro level, material compatibility between the polymer, metal, or ceramic is crucial. Loading conditions, such as shear and tension on the composite material, also affect its strength. Key selection criteria for adhesives include mechanical properties, environmental resistance, curing mechanism, and substrate compatibility.

- Surface treatments, adhesive types, joint design optimization, and environmental protection are important in composite joining. Surface treatments such as plasma treatment and chemical primers can be implemented as mitigation strategies to prevent corrosion. Hardened epoxies are used in adhesive modifications for impact resistance. Joint design must also be optimized to prevent damage and improve performance.

- Adhesively bonded joints are widely used in aerospace and automotive applications due to their lightweight, high strength, and fatigue resistance. Material compatibility is critical in adhesive applications, environmental durability must be verified, automation plays a key role in quality production, and the use of non-destructive testing methods, such as ultrasonics for quality control, is crucial for detecting hidden voids in adhesive applications on aircraft.

- Testing standards ensure the reliability, durability, and performance of adhesively bonded joints in industries such as aerospace, automotive, and construction. ASTM, ISO, SAE, and EN standards are primarily used to evaluate adhesively bonded joints. EN and NADCAP standards are also available. Additionally, common tests used for adhesively bonded composites include lap shear testing, wedge testing, peel testing, and fatigue testing.

- Adhesively bonded joints contribute to sustainability by enabling lightweight designs, reducing energy consumption, and minimizing waste compared to traditional mechanical fastening or welding methods. However, their environmental impact depends on the adhesive formulation, manufacturing processes, and end-of-life recyclability.

- The field of adhesively bonded joints is rapidly evolving, driven by advances in materials science, Industry 4.0 technologies, and sustainability demands. Future work could benefit from Industry 4.0, the rapid technological advancement that leverages artificial intelligence and robotic automation in adhesive selection. In Industry 4.0, the right adhesive can be selected using AI and machine learning.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

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