



Review of Adhesive Bonding in Aircraft Structures: Advances, Challenges and Future Trends

Malik Abdulwahab ^a, Ndubuisi Isaac Mbada ^a Muhammed Salihu Jimoh ^b Zakari Sharon Ocholongwa ^b

^a Department of Materials and Metallurgical Engineering, Air Force Institute of Technology, Kaduna

^b Department of Aerospace Engineering, Air Force Institute of Technology, Kaduna

Abstract

Adhesive bonding has emerged as a crucial joining method in the aerospace industry, offering advantages such as weight reduction, improved fatigue resistance, and enhanced corrosion resistance. Recent advances in adhesive materials, bonding processes, and quality-assurance techniques have further expanded the potential of adhesive bonding in aircraft structures. High-performance structural adhesives, including toughened epoxies, bismaleimide, and cyanate ester adhesives, have been developed to address extreme operating conditions. Multifunctional and smart adhesives that incorporate nanomaterials and self-healing capabilities are being explored to improve bonded-joint performance and durability. Advances in surface preparation, such as laser ablation, atmospheric pressure plasma treatment, and sol-gel processes, have improved bonding reliability. Out-of-autoclave processing and advanced curing methods have increased efficiency and reduced manufacturing costs. Extended non-destructive testing techniques, including phased array ultrasonic testing, active thermography, and terahertz imaging, enable more effective evaluation of bonding quality. However, challenges remain, including moisture ingress, thermal cycling, and the detection of kissing bonds. Future trends include self-healing and damage-tolerant adhesives, sustainable and recyclable bonding systems, and the integration of digital twin technology for process optimisation and quality control. The shift from post-process NDT to integrated structural health monitoring systems, together with AI-powered data analysis is expected to revolutionise the certification and maintenance of bonded aerospace structures.

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Corresponding author: muhammedsalihujimoh@gmail.com

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1. Introduction

Adhesive bonding is a method for joining similar or dissimilar materials [1]. Adhesive bonding offers several advantages over traditional joining methods, such as bolting, brazing, welding, and mechanical fasteners, because it can join diverse materials, enable permanent assemblies and simplified manufacturing. Adhesive joints can be applied to a wide variety of structures and withstand different types of loads [2]. Adhesive bonding technology enables design flexibility and can be integrated into single-piece workflows and mass production sequences [3]. Adhesive bonding has been used in aircraft wings and structures for over 75 years [1]. It has been applied to metallic and composite materials in primary aircraft structures, including skin-stringer, skin-rib and skin-spar joints. Despite significant advances, adhesive bonding continues to show considerable potential in the aerospace industry; however, limitations and challenges remain [4]. Aircraft bonding is an alternative to mechanical fastening because it reduces weight, improves fatigue resistance, and enhances corrosion resistance. Weight reduction improves fuel efficiency, while uniform stress distribution across bonded surfaces enhances fatigue resistance by minimising stress concentrations [5]. A key advantage is that bonding often requires little or no heat, producing minimal internal stress or deformation and preserving the adherents' macroscopic integrity. However, a major challenge is the bond line's relatively poor heat of adhesive bonding is the relatively poor heat resistance of the bond line compared to that of inorganic materials [3]. Recent progress has focused on improving the reliability, performance and sustainability of bonded aircraft structures. Major challenges include detecting and mitigating defects such as kissing bonds and porosity [6]. Researchers have investigated modification techniques, joint designs, and self-healing adhesives to improve bonding performance in aerospace applications [7]. Recent studies have also examined various joint configurations, adhesive materials and manufacturing methods, emphasising toughening strategies and defect detection [8]. Surface preparation remains crucial for achieving optimal bond strength and durability, while new testing techniques ensure compliance with industry standards [9]. Future trends involve the development of unified frameworks for defect assessment, advanced modelling methods and sustainable adhesive technologies [6]. The field continues to evolve, addressing the complex operating conditions in aerospace while aiming for enhanced reliability and predictability [7]. Although adhesive bonding has been extensively studied and applied in the aerospace industry, the rapidly evolving landscape of materials, technologies, and quality assurance methods requires an up-to-date synthesis of recent advances. Existing literature often focuses on isolated aspects such as adhesive materials, bonding processes, or non-destructive testing techniques. This review addresses that gap by comprehensively examining recent progress in adhesive bonding for aircraft applications, covering material innovations, bonding technologies, process improvements, advanced inspection methods, and emerging trends such as smart adhesives and digital twin integration. By consolidating multidisciplinary developments and identifying ongoing challenges, this review aims to be a practical resource for researchers and industry stakeholders seeking to improve the reliability, performance, and sustainability of bonded aerospace structures.

1.1. Advances in Materials and Technologies

Innovations in adhesive bonding in aircraft structures have led to significant improvements in weight reduction, corrosion resistance, and fatigue performance. Boeing's development of a surface preparation procedure (BAC 5555) in the early 1970s enhanced the durability of adhesively bonded aluminium alloy joints. This advancement, combined with improvements in adhesives and surface treatments, has led to enhanced mechanical properties, improved processing characteristics, and increased durability in humid or corrosive environments. The Primary Adhesive Bonded Structure Technology (PBAST) program was initiated in February 1975 to achieve a 20 percent reduction in maintenance and acquisition costs, as well as a weight saving for bonded assemblies instead of rivets. The program demonstrated that the damage tolerance and durability of bonded structures far exceeded those of riveted structures [10]. The use of composite materials as a replacement for commonly used metals is increasing in the aerospace industry. The need for lightweight, high-stiffness structures with good corrosion resistance and fatigue durability influences this. Hybrid joints, which combine mechanical fasteners and adhesive bonding, offer greater residual strength and design flexibility than traditional joining methods [11]. These innovations have made adhesive-bonded joints crucial to modern engineering, providing enhanced fatigue performance and improved stress distribution, leading to widespread adoption in engineering [12].

1.2. Advances in Adhesive Materials

1.2.1 High-performance structural adhesives

Recent advances in aircraft adhesive systems have focused on various methods to overcome the inherent brittleness of epoxy resins. One widely explored approach is rubber toughening, which involves incorporating different types of rubber particles and modified rubbers into epoxy matrices [13]. The formation of Interpenetrating Polymer Networks (IPNs) has gained attention, offering improved fracture toughness while maintaining high service temperatures [14]. Another key strategy involves the integration of nanomaterials. Wazalwar et al. (2021) reviewed the use of 2D nanomaterials, such as graphene, to enhance the mechanical properties of epoxy composites for aerospace applications. The authors highlighted that Graphene, Transition Metal Dichalcogenides (TMDs), and hexagonal Boron Nitride (hBN) possess significant stiffness, contributing to the formation of stronger epoxy composites. Further supporting this, Khalid et al. (2023) found that Graphene/epoxy nanocomposites enhance the fracture toughness of epoxy adhesives through mechanisms like crack pinning, crack deflection and the formation of large deformation zones [15]. However, for these laboratory findings to be industrialised, challenges related to standardisation and potential health and environmental concerns must be addressed [16]. In addition to 2D materials, nanoparticle toughening using surface-modified silica nanoparticles has shown promise in enhancing mechanical properties and fracture toughness without compromising strength or modulus [17]. Researchers have also investigated synergistic effects by combining toughening agents. For example, the combination of thermoplastic rubbers and core-shell rubber particles has been shown to significantly improve critical fracture energy and impact strength [18]. Alongside toughening, recent research has focused on improving the thermal stability and bond performance of adhesives for high-temperature aerospace applications.

For extreme environments, such as thermal protection systems in hypersonic vehicles, Ultra-high temperature ceramics (UHTCs) are being investigated. Composites based on ZrB₂-HfB₂-SiC for example, have shown promise due to their high oxidation resistance and improved thermos-mechanical properties [19]. Bismaleimide (BMI) and cyanate ester (CE) adhesives are notable for their excellent thermal performance. BMI composites offer high strength and rigidity at temperatures up to 260 °C, placing them between epoxy and polyimide in terms of thermal stability and moisture absorption [20]. BMI adhesives can be modified to enhance toughness and processability through the addition of components like Poly(phthalazinone ether nitrile ketone) (PPENK) and vinyl-terminated butadiene acrylonitrile (VTBN) [21]. BMIs can also be combined with other resins, such as cyanate esters, to create high-performance adhesives with improved processing characteristics [22]. Research has focused on optimising BMI formulations for specific applications, studying their mechanical properties, environmental resistance and offgassing behaviour [23]. Modern approaches to BMI processing aim to balance high temperature performance with manufacturability, sometimes requiring trade-offs between properties and processability [24]. Advanced thermoplastic adhesives, particularly those based on polyether-ether-ketone (PEEK) and polyether-ketone-ketone (PEKK), also offer promising capabilities. These high-performance polymers exhibit excellent mechanical properties, thermal stability and recyclability [25]. PEEK and PEKK composites demonstrate potential for out-of-autoclave processing and rapid manufacturing techniques. Aveneta et al. (2020) observed three bonding regimes during interface formation when studying the adhesion kinetics of PEKK [26]. Additively manufactured PEEK and carbon fibre reinforced PEEK can be joined using ultrasonic welding with integrated energy directors, achieving high bond strengths comparable to the bulk material [27]. These advancements in thermoplastic adhesives offer opportunities for developing recyclable, weldable and efficiently processable materials for various industrial applications. Thermoplastic composites are gaining popularity in aerospace applications due to their formability, short production cycles and recyclability [28].

1.2.2 Multifunctional and smart adhesives

Carbon nanotubes (CNTs) and graphene have emerged as promising nanomaterials for enhancing the properties of fibre-reinforced polymer (FRP) composites. These nanoparticles can significantly improve mechanical properties, including interlaminar fracture toughness and impact resistance [29]. Additionally, CNTs and graphene enable multifunctional capabilities such as structural health monitoring (SHM) by increasing electrical conductivity and providing self-sensing properties [30, 31]. These nanoparticle-enhanced composites exhibit improved thermal conductivity and electromagnetic interference shielding [32]. However, challenges remain in effectively incorporating nanomaterials into FRP composites using scalable and cost-effective manufacturing processes [31]. Despite these challenges, CNT and graphene-based composites show great potential for various applications in the aerospace industry [32]. Recent developments in adhesive technology have developed Self-healing mechanisms into tangible material innovation. Self-healing adhesives are emerging as a promising technology for enhancing the durability and safety of aerospace components. These materials can repair damage through various mechanisms, including microcapsule-based, vascular and intrinsic healing [33]. Vascular networks, inspired by biological sys-

tems, offer advantages such as addressing varying damage magnitudes and allowing indefinite replenishment of healing agents [34]. Current research has validated the ability of these composites to autonomously arrest crack propagation and recover mechanical integrity without compromising functionality [35]. The integration of these mechanisms into the adhesive matrix represents a significant leap in material engineering, moving beyond static bonding agents toward active, responsive material systems [36].

1.3. Advances in Bonding Process Technology

1.3.1 Surface preparation techniques

The durability of bonded composite materials is critically dependent on their initial surface preparation. Several advanced methods are being developed to replace traditional, often hazardous techniques with more precise and environmentally friendly alternatives. Laser ablation has become a prominent technique for preparing surfaces of various materials, including metals, ceramics and polymers. It offers superior precision, reproducibility, and environmental friendliness compared to traditional methods [37, 38]. For metals, laser ablation can improve the bonding strength and corrosion resistance by increasing surface roughness and wettability [37]. In polymers, ultra-short laser ablation can produce high-quality micro- and nanostructures with various functional applications, such as enhanced adhesion and self-cleaning properties [39]. The success of this method hinges on understanding laser-material interactions and optimising process parameters [40]. Laser ablation demonstrates significant potential for achieving precise, clean, and repeatable surface preparation across different material types. Similarly, atmospheric pressure plasma treatment effectively enhances the surface wettability and adhesion of various materials used in the aerospace industry. Studies report significant reductions in water contact angles and increased surface energy on thermoplastic composites [41], polyethylene terephthalate [42], and high-impact polystyrene [43]. This improvement is attributed to the formation of oxygen and nitrogen polar groups on the surface, enhancing adhesion properties [41, 42]. Plasma processing offers advantages over conventional wet chemistry approaches, being highly selective, environmentally friendly and cost-effective. It can modify both surface chemistry and topography, allowing for precise control of wettability from super-hydrophobic to super-hydrophilic [44]. Sol-gel processes offer another key solution for creating stable, adhesion-promoting layers on metallic substrates. These processes involve hydrolysis and poly-condensation reactions to enhance adhesion for various applications [45]. A significant advantage is their potential to replace hazardous surface treatments and chromate-containing primers, improve worker safety and reduce environmental impact [46]. The efficacy of sol-gel treatments depends on factors such as surface pre-treatments, substrate composition and coating formulation [45, 46]. This chemistry enables the production of diverse materials, including nanoparticles, fibres and coatings with functional properties like fire resistance and hydrophobicity [47]. For instance, multi-layer oxides synthesised via sol-gel have demonstrated improved corrosion resistance on aluminium substrates used in aircraft components [48].

1.4. Curing and Assembly Technologies

Beyond surface preparation, advancements in curing and assembly technologies are crucial for efficient and reliable composite manufac-

turing. These innovations focus on reducing costs, shortening cycle times and improving final product quality. Out-of-Autoclave (OoA) processing, particularly using vacuum-bag-only (VBO) prepregs offers significant cost and efficiency benefits compared to traditional autoclave methods in aerospace composite manufacturing. OoA processes can produce parts of comparable quality to autoclave-cured components while drastically reducing manufacturing costs and time [49]. Recent advancements, such as the use of nanoporous materials, have enabled the production of void-free, autoclave-grade composites without an autoclave, demonstrating equivalent or improved mechanical properties [50]. VBO-oven cure techniques have been optimised to enhance inter-laminar shear strength and minimise void content in composite laminates [51]. Despite challenges in ensuring consistent quality products, OoA methods offer advantages, including reduced cycle time, lower investment costs, and decreased energy consumption compared to autoclave processing [52]. These developments position OoA techniques as an attractive alternative to conventional autoclave fabrication for aerospace applications. Further innovation is evident in advanced curing techniques that serve as alternatives to conventional methods. Induction heating, microwave curing and integrated heating elements provide quick and targeted curing options, especially useful for repairs (Collinson et al., 2022; Abliz et al., 2013). These approaches offer benefits such as accelerated heating, precise control of exothermic reactions and lower energy use (Collinson et al., 2022). For example, induction heating, utilising electrically conductive or ferromagnetic fillers, allows for selective heating and activation of specific effects in polymers (Mariani and Malucelli, 2023). Portable hot bonders with local heating elements enable on-site repairs of composite components, increasing flexibility in maintenance tasks (Bazheryanu et al., 2020). While these methods show potential for reducing costs and boosting throughput, challenges remain in ensuring uniform cure levels and ease of application (Collinson et al., 2022). Ongoing research seeks to refine these techniques for broader industrial use in composite manufacturing and repair. In the assembly phase, robotics and automation are crucial for enhancing consistency and reducing human error. Automated systems for adhesive dispensing and component assembly significantly improve both efficiency and product quality [53]. AI-enhanced vision systems, for example, facilitate precise glue dispensing on large parts by using deep learning for profile recognition and quality control [54]. Lean robotics principles are also being applied to optimise task scheduling, simplifying operations and eliminating inefficiencies in adhesive dispensing [55]. The integration of medium-sized robots with smart tools and human-robot collaboration facilitates automated assembly and inspection of composite fuselage panels [56]. The implementation of these robotic solutions, which incorporate features like real-time measurements and multimodal perception systems, enables Aerospace manufacturers to achieve greater precision, flexibility and cost effectiveness in their production processes.

1.5. Advances in Quality Assurance and Monitoring

Ensuring the integrity of bonded composite structures requires robust quality assurance protocols. These are increasingly supported by advanced techniques for both real-time process monitoring during manufacturing and comprehensive post-manufacturing inspection.

1.5.1 In-situ process monitoring

In-situ process monitoring provides real-time data during manufacturing, enabling immediate process optimisation and enhanced quality control. Fibre Bragg Grating (FBG) sensors embedded directly within bond lines are highly effective for real-time monitoring of temperature, strain, and cure state in composite materials. These sensors offer high sensitivity and electromagnetic interference resistance [57]. Applications include monitoring epoxy curing processes and strain changes at cryogenic temperatures, providing valuable data for magnetic reliability and maintainability [57]. In carbon fibre reinforced polymer (CFRP)/aluminium alloy bonding, encapsulated FBG sensors enable monitoring of different curing stages, including polymerisation and residual strain [58]. Furthermore, polyimide-coated FBGs allow for high-temperature monitoring up to 300°C [59], while small-diameter optical fibre FBG sensors can detect subtle strain changes during vacuum-assisted resin infusion (VARI) processes [60]. This technology provides crucial data for optimising curing processes and improving composite manufacturing techniques. Another powerful method is Dielectric analysis (DEA), which monitors in real-time ionic conductivity changes during the curing process of thermoset adhesives. It enables in-situ monitoring of epoxy resin curing by measuring dielectric properties as crosslinking reactions occur [61, 62]. DEA can detect cure changes for crosslink densities below 80 percent and can be correlated with reaction kinetics derived from differential scanning calorimetry (DSC) [62]. The technique is suitable for online monitoring in various manufacturing processes, including injection moulding and liquid composite moulding [62, 63]. The ability to determine gelation time and predict the degree of cure is crucial for optimising curing time and ensuring product quality [63]. Additionally, recent developments in printed paper sensors show promise as cost-effective, biodegradable alternatives to commercial DEA sensors [64].

1.6. Extended Non-Destructive Testing (NDT) for Bonded Structures

Beyond in-situ monitoring, advancements in post-manufacturing non-destructive testing (NDT) have significantly improved the evaluation of bond quality in composite structures. Advanced ultrasonic techniques such as Phased Array Ultrasonic Testing (PAUT) and Air-Coupled Ultrasonic Testing (ACUT) offer effective solutions for inspecting complex geometries and non-contact inspection. PAUT has successfully detected defects in thick additively manufactured components, identifying flaws as small as 0.25 mm in diameter [65]. For thin curved components, guided waves have shown promise in detecting defects down to 1 mm [65]. To inspect welds with complex curvature, flexible PAUT probes and semi-automatic scanners have been developed to [66]. PAUT is widely used in various industries for weld inspections, flaw detection, and corrosion inspections, offering advantages such as rapid, safe, and accurate visualisation of defect characteristics [67]. For its part, ACUT has proven effective for investigating composite defects, with statistical analysis and machine learning techniques improving delamination detection accuracy in composite structures [68]. Active thermography, encompassing techniques like pulsed, step-heating, and lock-in thermography, provides a rapid and effective method of inspecting large areas for defects. Step-heating and lock-in thermography are particularly promising for inspecting thick composite structures with low surface emissivity [69]. A novel

approach combining pulsed phase and lock-in thermography enables fast, quantitative assessment of damage in aircraft composites in under a minute [70]. Recent advances in signal processing techniques have improved defect detection and characterisation in pulsed thermography [71]. For spot weld inspections in automotive manufacturing, inductive heating has proven to be the most suitable technique, allowing for both front and back heating, while principal component analysis and fast Fourier transform provide valuable post-processing information [72]. These developments demonstrate the versatility and effectiveness of active thermography in various industrial applications. Shearography and Digital Image Correlation (DIC) are advanced optical NDT techniques. Shearography is adept at detecting small defects, with recent research developing models to determine the smallest detectable defect size and depth under various loading conditions [73]. It is also effective for inspecting thick composite materials, such as glass fibre-reinforced polymer laminates [74]. To address challenging effects like kiss-bonds, specialised methods such as dynamic lines such as dynamic line-scan thermography, are also being developed for high-speed detection [75]. DIC has proven valuable in measuring surface displacements and strains across a wide range of structural components in laboratory settings, offering benefits such as non-invasive operation, full-field measurement, and high precision [76]. Both techniques show high sensitivity to disbands, especially when combined with thermal or vacuum loading. Terahertz (THz) imaging is emerging as a powerful non-destructive technique for detecting bonding defects and assessing adhesive layers in various materials. THz time-domain imaging can inspect multilayered structures and determine layer thicknesses with high resolution [77]. An improved imaging method based on statistical characteristics can detect bonding defects as small as 50 μm in ceramic matrix composites [78]. THz waves can also diagnose debonding defects in heat-resistant structures by analysing time-windowed data corresponding to the adhesive layer [79]. This technique has applications in security imaging, automotive paint quality control, aerospace testing, and biomedical diagnostics. Resonant tunnelling diode (RTD) technology is promising for developing compact, low-cost THz imaging systems [80]. These advancements underscore the growing potential of THz imaging for quality control across multiple industries.

2. Challenges and Limitations

2.1. Material related challenges

Moisture ingress, or hydrothermal ageing, significantly impacts the performance of composite structures and adhesive joints. Water absorption can occur through the adhesive, substrate, interface, or cracks and pores, leading to reduced mechanical properties and plasticization of the adhesive [81]. This degradation is often more rapid in joints than in bulk adhesives due to multiple diffusion paths [81]. Hydrothermal ageing affects various components, particularly sandwich panels and adhesive-bonded joints in industries like wind turbines and aerospace [82]. In glass fibre-reinforced vinyl ester composites, moisture-induced ageing significantly impacts the fibre-matrix interface and overall mechanical performance [83]. Long-term exposure to moisture and humidity results in decreased strength and interlayer shear strength in fibre-reinforced polymer (FRP) composites [84]. For FRP/steel joints, moisture can initially strengthen the bond but may lead to long-term strength reduction [84]. Adhesively bonded joints in aircraft face significant challenges due to extreme

temperature changes and cyclic loading. Factors like load levels, adhesive type, joint geometry, and substrate material influence creep behaviour in adhesives [85]. Fatigue failures are often induced by accelerated thermal cycling, with mismatches in thermal expansion coefficients contributing to stress on joints [86]. Soft adhesive systems, crucial in advanced applications, require special consideration for fatigue failure mechanisms and lifetime prediction [87]. Various methods to enhance fatigue performance of adhesively bonded composite joints have been studied, including modifications to adherends, adhesives, and joint configurations [88]. Understanding the interplay between fatigue and creep is essential for predicting joint behaviour under these conditions [85]. Monitoring crack initiation and propagation remains a challenge in assessing the fatigue performance of adhesive joints [88]. Recent research highlights the challenges and innovations in developing adhesives with balanced properties. Shape memory polymers (SMPs) offer potential solutions to the trade-offs between adhesion strength and switchability in smart dry adhesives [89]. For hydrogels, structural design approaches like integrated, layered, and gradient structures are being explored to achieve both adhesion and toughness [90]. Vitrimers, a new class of materials with dynamic covalent bonds, present an opportunity to overcome the durability-reprocessability trade-off in polymers [91]. In the realm of supramolecular chemistry, small-molecule self-assembly is emerging as a promising approach for developing adhesives with precise structures and smart functions like responsiveness and adaptiveness [92]. These advancements demonstrate ongoing efforts to address the inherent material trade-offs in adhesive formulation, particularly in balancing strength, toughness, and performance under various conditions.

2.2. Process related challenges

Surface preparation is crucial for achieving reliable adhesive bonding in industrial applications. The effectiveness of adhesion depends on both mechanical and chemical bonding mechanisms, which are influenced by surface energy and the ability of the adhesive to wet the substrate [93]. Proper surface treatment can remove contaminants, optimise surface topography, and enhance adhesive spreading, thereby improving bonding strength [94]. However, achieving consistent and perfect surface preparation in industrial settings remains challenging due to the sensitivity of bonding to minute contaminations that can be difficult to detect before bond formation [95]. To address this, researchers suggest using substrate water contact angle measurements as a predictive tool for adhesion quality [93]. Additionally, combining different surface treatment methods can significantly improve preparation quality and mitigate the limitations of single treatment approaches [94]. Future research should focus on developing multi-method detection approaches and advanced modelling techniques to enhance reliability in adhesive bonding [95]. Residual stresses pose significant challenges in manufacturing and adhesive bonding processes. These stresses can develop during curing, especially when joining materials with different thermal expansion coefficients, potentially weakening joints before loading [95]. In metal additive manufacturing, residual stresses can lead to geometrical distortions and impact fatigue life [96]. Various methods exist for determining and controlling residual stresses across different materials, including metallic alloys, polymers, and composites [97]. Adhesive bonding faces additional challenges such as ensuring uniform cures in thick bondlines and complex geometries [95]. Recent research has focused on

joint configurations, manufacturing techniques, and defect detection in adhesively bonded joints for composite materials [98]. Addressing these issues requires advanced modelling techniques, multi-method detection approaches, and further research into defect correlation and sustainable adhesive technologies [6]. Bonded repairs in aerospace structures present significant challenges, particularly in non-factory environments. Surface preparation and contamination control are critical factors affecting repair durability. Moisture and contaminants can lead to reduced joint strength and catastrophic adhesive failure, with water ingress occurring faster in joints than bulk adhesives [81]. Despite these challenges, bonded repairs offer high-strength recovery and improved aerodynamics for composite structures [99]. For cracked plates, bonded composite patches have shown promise in reducing stress-intensity factors [100]. Ongoing research focuses on optimization, durability, and reliability of flush repairs, with innovative designs potentially reducing repair size while maintaining strength [99]. These advancements aim to improve the reliability and long-term performance of bonded repairs in challenging environments.

2.3. Challenges in Quality assurance and NDT

Kiss-bonds are difficult to detect with conventional NDT methods like ultrasound; their occurrence poses a serious threat to modern aircraft adhesive joints by necessitating additional riveting that increases weight and weakens surrounding materials [101]. Adhesive bonding is a versatile joining method with applications across industries, but it faces challenges in detecting defects and ensuring reliability [6]. Common defects include disbonds, voids, porosity, and poor adhesion, with kissing bonds being particularly difficult to detect. Non-destructive inspection (NDI) techniques such as ultrasonic methods, shearography, and thermography are used to identify these defects, but detecting poor cohesive and adhesive properties remains challenging [102]. Lamb waves have shown promise in structural health monitoring (SHM) of adhesive joints, with ongoing research in signal processing, machine learning, and simulation methods (Ramalho et al., 2021). However, there is a lack of studies specifically addressing weak adhesion monitoring using Lamb waves [103]. Future research should focus on developing multi-method detection approaches, advanced modelling techniques, and sustainable adhesive technologies to improve reliability and support a circular materials economy [95]. Non-destructive testing (NDT) of composite materials is crucial for ensuring structural integrity in aerospace and other industries [104]. Common defects in adhesive joints include disbonds, voids, and poor cohesive/adhesive strength [102]. Various NDT techniques are employed, including ultrasonic testing, thermography, and shearography, each with its specific capabilities and limitations [105]. While detecting flaws is achievable, quantifying their impact remains challenging. Current research focuses on developing intelligent and automated inspection systems for more accurate and efficient data processing [106, 105]. Monitoring interfacial properties before cure and assessing environmental degradation during service are areas of ongoing investigation. Despite advancements in NDT methods, the expertise of well-trained personnel remains crucial for the effective implementation of these methods [102]. The inspection of complex structures in aerospace applications presents significant challenges, necessitating advanced non-destructive testing (NDT) methods. Data fusion of multiple NDT techniques, coupled with emerging technologies like artificial intelligence and digital twins, can enhance inspection accuracy and efficiency [107]. Common defects

in adhesive joints include disbonds, voids, and poor surface preparation, which can be detected using ultrasonic methods, shearography, and thermography [102]. Automated systems integrating robotic technologies with NDT methods, such as active thermography, visual inspection, and 3D scanning, offer promising solutions for aircraft inspection [108]. Drone-based NDI is gaining traction for inspecting large and complex structures, providing benefits like reduced inspection time, cost, and personnel safety risks. However, challenges remain in reliably detecting defects using drone-based systems [109]. These advancements aim to improve defect detection accuracy, reduce downtime, and enhance overall safety in aerospace maintenance.

2.4. Challenges in certification and predictive modelling

The aerospace industry's slow adoption of new adhesive technologies is largely due to the complex and costly certification process for primary structures [4]. This process requires extensive testing and validation, which can take years and cost millions. Recent research has focused on improving adhesive performance, bonding techniques, and self-healing methods for aerospace applications [7]. Various models and failure theories for adhesive joints have been reviewed, including analytical methods, fracture mechanics approaches, and probabilistic methods [110]. However, the lack of standardized experimental procedures across different industries has led to additional costs and barriers in the certification process [4]. To address these challenges, efforts are being made to develop high-fidelity datasets and validation protocols for advanced computational methods, particularly for composite structures under various environmental conditions [111]. These initiatives aim to bridge the gap between research and the adoption of novel structural analysis techniques by industry. Recent research has highlighted the challenges in predicting the long-term degradation and failure of adhesively bonded joints, particularly under environmental and fatigue conditions. Environmental factors like temperature and moisture can significantly impact joint durability and fatigue behaviour, leading to premature and unpredictable failures [112]. While various analytical and numerical approaches exist for modelling joint behaviour, including Classical Analytical Methods, Cohesive Zone Method, and Finite Fracture Mechanics, each has limitations in accurately predicting real-world performance [110]. Current experimental procedures often fail to align with industrial applications, necessitating the development of advanced characterisation methods that consider sustained loads during environmental exposure [113]. Multi-scale modelling approaches offer promising avenues for predicting long-term durability of composite materials under various environmental conditions, but further research is needed to integrate multiple stressors and improve predictive capabilities [114].

3. Future Trends

3.1. Smart and sustainable materials

3.1.1 Self-healing and damage-tolerant adhesives

Self-healing adhesives are gaining prominence in aerospace applications due to their ability to autonomously repair micro-cracks and extend the service life of bonded joints [7]. Two main approaches for self-healing systems are microcapsule-based and vascular network-based methods [115]. Vascular networks, inspired by biological sys-

tems, offer advantages such as addressing varying damage magnitudes and allowing indefinite replenishment of healing agents [34]. However, the preparation of healing agents for vascular systems remains challenging [116]. Recent advancements in additive manufacturing have enabled the creation of more complex network configurations, optimising fluid distribution and healing potential [34]. While self-healing technology shows promise for aerospace components, further research is needed to improve reliability, predictability, and performance under various conditions such as fatigue, impact, and ballistic stress [36, 116].

3.2. Adhesives with integrated sensing (multifunctionality)

Recent advancements in structural health monitoring (SHM) for aerospace applications have focused on integrating sensing capabilities directly into materials and structures. Self-sensing composites, created by incorporating conductive nanomaterials like carbon nanotubes and graphene into matrices, offer intrinsic sensing through piezoresistivity [117, 118]. These smart materials enable real-time monitoring of structural integrity, enhancing safety and efficiency in aerospace operations [119]. Embedded sensors play a crucial role in SHM systems, allowing continuous measurements of material properties [120]. However, challenges remain in sensor integration, data processing, and interfacing with digital systems [118, 120]. Future developments aim to combine advanced materials, artificial intelligence, and blockchain technology to create comprehensive SHM systems for the "factory-of-the-future" [118]. This integration of smart materials and sensing technologies promises to revolutionize structural monitoring across various industries.

3.2.1 Sustainable and recyclable bonding systems

The growing focus on sustainability has led to increased research into recyclable adhesive technologies. Debonding-on-demand adhesives enable selective weakening of bonds, facilitating disassembly, repair, and recycling of materials [121]. Various approaches have been explored, including reversible adhesive systems, electrically debondable adhesives, and the use of fillers triggered by external stimuli like heat or magnetic flux [122]. The incorporation of imine-based polyols into polyurethane adhesives has shown promise, offering comparable performance to traditional adhesives while allowing for enhanced recyclability through acidic hydrolysis [121]. The development of covalent adaptable networks (CANs) in thermoset adhesives is another strategy being investigated to improve recyclability [123]. These advancements in sustainable adhesive technologies have significant implications across various industries, including aviation, automotive, and electronics, contributing to resource conservation and promoting a circular economy [124, 121].

4. The Digital Twin and Industry

4.1. Digital twin for bonded joint

The Digital Twin concept, a virtual representation of physical objects or processes, is gaining prominence in Industry 4.0 [125]. It enables real-time monitoring, optimization, and control of manufacturing processes by creating a virtual copy of the physical world [126]. Digital

Twins rely on sensors and IoT technologies to collect data from physical assets, which is then processed to create accurate virtual models [125]. These models can be used to predict performance, optimize processes, and ensure quality control [127]. The Digital Twin framework consists of 13 key characteristics, including physical and virtual entities, environments, and processes [128]). While the technology shows promise, further research is needed in areas such as perceived benefits, use-cases, technical implementations, and data ownership to fully realize its potential across the product life-cycle [128, 127].

4.2. Fully automated and adaptive production

Machine vision technology is revolutionizing aerospace manufacturing by enhancing quality inspection, automation, and adaptive production processes [129]. Adaptive automation systems dynamically allocate functions between humans and machines, improving efficiency and addressing traditional automation challenges [130]. In welding applications, adaptive intelligent systems use sensors, process modeling, and artificial intelligence to adjust parameters in real-time, ensuring optimal results despite deviations from nominal conditions [131]. Machine vision's ability to acquire and analyze images automatically enables various industrial applications, including component inspection, process control, and robotic guidance [132]. These technologies are driving the development of "lights-out" factories, where adaptive robotic systems use machine vision and sensors to adjust processes for minor variations, ensuring consistent quality in aerospace manufacturing [129, 131].

5. Additive Manufacturing (3D Printing) in Bonding

Additive manufacturing (AM) has revolutionized the aerospace industry by enabling the production of complex, customized parts with improved efficiency and reduced waste [133]. The technology allows for the creation of functionally graded materials (FGMs) and structures (FGSs) with tailored properties, offering advantages in various applications including aerospace [134]. AM's ability to fabricate intricate shapes and high strength-to-weight ratio components makes it particularly valuable for aerospace applications [135]. Recent advances in adhesive bonding techniques for 3D-printed parts have further expanded AM's potential, with customized joint geometries and reinforcing materials enhancing bonding strength. The integration of AM with other technologies, such as optimized printing parameters and surface treatments, shows promise for improving overall performance of aerospace components [136]. As AM continues to evolve, it is expected to play an increasingly significant role in aerospace manufacturing, offering new possibilities for design and production.

5.1. From post-process NDT to integrated SHM

5.1.1 Nervous system airframe

Structural health monitoring (SHM) systems using embedded sensors are gaining prominence in aircraft maintenance, transitioning from periodic inspections to continuous condition-based monitoring [137]. Fiber Bragg Grating (FBG) sensors show great potential for damage detection in metal aviation structures [138]. Various SHM techniques have been developed, including vibration methods, strain-based fiber

optics, guided waves, and acoustic emission. These systems aim to detect incipient damage, avoid severe structural issues, and optimize maintenance schedules [139]. Embedded sensors (ESs) enable continuous monitoring of structural integrity, but their integration is limited by processing technology and material composition [120]. While sensor technology has remained relatively stable, algorithm improvements have driven SHM advancements. Reliability, demonstrated through probability of detection analysis, remains a key challenge for widespread implementation of SHM systems [139].

6. AI-Powered NDT and Data Fusion

The integration of AI, machine learning, and advanced technologies is revolutionizing non-destructive testing (NDT) in aerospace and other industries. AI-driven systems enhance defect detection accuracy and enable rapid analysis, significantly improving inspection efficiency [140, 141]. Data fusion techniques combine multiple NDT methods, offering a more comprehensive perspective on flaws and generating large datasets for robust interpretation [107]. The concept of digital twins, which creates virtual replicas of structures, facilitates real-time monitoring and predictive maintenance [107, 141]. AI-enhanced NDT automates data analysis, enables predictive maintenance, and supports data-driven decision-making. While these advancements promise improved safety and cost-effectiveness, challenges remain in data quality, ethical considerations, and regulatory standards [142]. Overall, AI-powered NDT is shaping a smarter, more resilient aerospace maintenance ecosystem [140].

6.1. Certification through virtual testing

The aerospace industry is moving towards increased use of modeling and simulation (M and S) for certification and qualification (C and Q) to reduce costs and development time [143]. This shift, known as Virtual Certification, aims to predict physical models and system behavior more accurately, limiting rework and enabling optimal design within time constraints [144]. The Digital Twin paradigm, integrating high-fidelity simulation with on-board health management systems and historical data, is proposed to address the extreme requirements of future vehicles [145]. Virtual Testing methodologies are being implemented to predict mechanical behavior across different scales of the testing pyramid, with hybrid simulation-physical testing approaches supporting both rapid sizing and high-fidelity analysis [146]. These advancements in M and S are expected to demonstrate safety and performance through simulation, drastically reducing the time and cost of certification in the aerospace sector.

7. Conclusion

Adhesive bonding has evolved into a cornerstone of modern aircraft design, driven by advancements in materials, bonding processes, quality assurance, and inspection technologies. High-performance adhesives ranging from rubber-toughened epoxies and nanomaterial-enhanced systems to high-temperature thermosets and recyclable thermoplastics are delivering greater durability, thermal stability, and multifunctionality. Complementary innovations in eco-friendly surface treatments, rapid curing methods, and automated assembly have improved manufacturing efficiency and consistency, while real-time monitoring

and advanced non-destructive testing ensure bond integrity and performance throughout a structure's service life. Despite these achievements, significant challenges remain. Environmental degradation, surface preparation inconsistencies, and the difficulty of detecting sub-critical defects like kissing bonds continue to limit reliability. The complexity and cost of aerospace certification slow the adoption of new bonding technologies, while predicting long-term performance under operational conditions remains a critical research priority. Addressing these barriers demands integrated progress in materials engineering, process control, inspection methods, and regulatory frameworks. Emerging trends signal a transformative future. Self-healing and sensor-embedded adhesives, sustainable and recyclable bonding systems, adaptive automation, and additive manufacturing are converging with Industry and Digital Twin technologies to redefine aerospace manufacturing and maintenance. This vision points to aircraft assembled by intelligent, collaborative robots applying precision-engineered adhesives that not only bond but also sense, report, and autonomously repair damage. Continuous, data-driven monitoring will replace periodic inspections, while virtual certification—powered by high-fidelity simulation and real-world sensor feedback—will streamline development and reduce costs. In this future, bonded aircraft structures will function as living, adaptive systems: lighter, stronger, more efficient, and more sustainable, enabling the aviation industry to focus human expertise on innovation rather than routine maintenance.

Conflict of interest

The authors declare there is no conflict of interest

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