



Review on composite bonding repairs: Scientific challenges on machining, surface preparation, and structural health monitoring

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ABSTRACT

Adhesively bonded repairs of thermoset fiber-reinforced polymer composites offer structural and weight advantages over mechanical fastening; however, they are generally not fully certified for primary load-bearing structures. This review evaluates the primary factors contributing to this lack of certification by focusing on surface and subsurface damage introduced during conventional machining, inconsistent or inadequate surface preparation. In addition, the limited capability of non-destructive testing techniques to detect all bond-line defects, quantify bond strength, and assess bond quality is also discussed. This review also examines the damaged material removal and surface preparation processes used in composite bonded repairs, comparing conventional machining with non-conventional approaches. Emphasis is given on using the abrasive water jet machining (AWJM) process for damage removal and surface preparation within a single repair process. The process of controlling induced damage, mitigation of thermal degradation, and improving surface morphology before bonding is also discussed. Additionally, bonded repairs remain sensitive to defects originating from patch fabrication, curing, environmental exposure, and in-service loading; improvements in machining and thus surface preparation alone cannot guarantee repair quality. Therefore, the role of structural health monitoring (SHM) as a necessary complementary process for certification is also discussed. The review also provides a comprehensive assessment of fiber-optic, piezoelectric, and piezoresistive sensing techniques applied to composite bonded repairs, evaluating their ability to detect damage initiation, propagation, and localization throughout the service life. It further identifies key technical barriers and outlines future research pathways toward the reliable qualification and certification of bonded composite repairs in primary aerospace structural applications.

1. Introduction

The global composite materials market has exhibited continuous growth across major end-use sectors in recent years. Market analysts project sustained expansion through the 2030s at compound annual growth rates in the mid to high single digits. This is mainly driven by increasing demand in aerospace, automotive, wind energy, infrastructure, marine, and electronics applications [1,2]. This trend reflects widespread adoption of fiber-reinforced polymers (FRPs) due to their

high specific strength and stiffness, corrosion resistance, durability, design flexibility, and superior fatigue resistance [3]. These properties enable enhanced performance, reduced weight, and lower lifecycle costs compared with conventional materials in demanding structural applications [4–6]. Furthermore, the thermo-mechanical properties of composites can be tailored by altering ply stacking sequence and fiber orientation. This also allows for meeting specific loading conditions (stiffness, strength and fatigue resistance) without the need for overly conservative design allowances [7,8]. However, while such tailored

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architectures provide outstanding structural efficiency, the brittle nature of polymer matrix composites and the absence of through-thickness reinforcement render them particularly vulnerable to impact-induced damage [9,10].

Damage in FRPs develops through multiple interacting mechanisms, including matrix cracking, fiber breakage, and delamination, which reduces stiffness and load-bearing capacity [15,16]. These damage modes originate from numerous, frequently occurring sources and should therefore be regarded as common rather than exceptional.

Composites can comprise up to 53% of an aircraft's structural weight [17]. Parts of the airframe are continuously exposed to different sources of damage. According to Fig. 1, typical hazards can be encountered during service, ranging from routine ground operation zones. For example, equipment collisions and accidental tool drops, environmental and in-flight risks like hail indentations, lightning strikes and bird strikes. Additionally, it highlights specific structural compromises, including skin/spar damage and foreign object damage. Of particular concern, many impact events cause Barely Visible Impact Damage

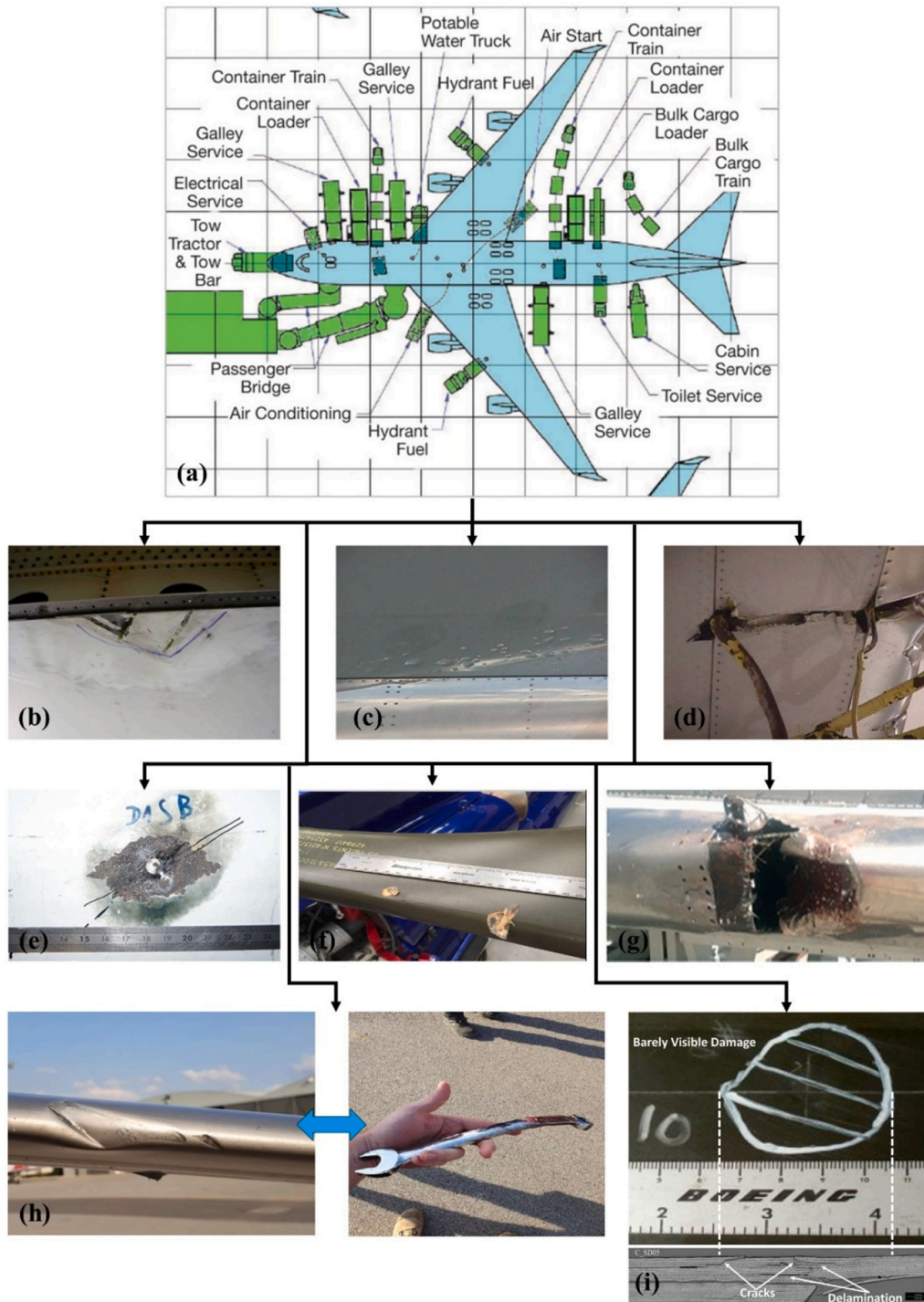


Fig. 1. Representative service-induced damage sources and examples in composite aircraft structures: (a) possible impact damage locations during routine ground operations [11], (b) ground equipment damage to the top spar [12], (c) hail indentations [12], (d) skin/spar damage [12], (e) severe lightning strike [13], (f) foreign object damage to the rotor leading edge blade [14], (g) bird strike on the horizontal tail [13], (h) tool damage [14], (i) BVID [12].

(BVID), which is often not detected during visual inspection. Although it may appear harmless at the surface, BVID can involve internal damage that can propagate unpredictably, resulting in significant structural degradation and elevated safety risks [18,19]. Consequently, timely repair or replacement of the structure is crucial to prevent further crack propagation, restore load-carrying capacity, and ensure compliance with design requirements and safety standards. The decision to repair or replace damaged components depends on a balance of economic, environmental, and technical factors. From a cost standpoint, repair is often more viable, with typical thermoset composite repair operations estimated at \$15,000-\$150,000 per component, representing only 8-25% of typical replacement costs [20]. From an environmental standpoint, repair minimizes material waste and reduces the embodied energy and resources associated with fabricating new components [21]. From a technical perspective, the decision to repair or replace a component is governed by the relationship between damage severity and allowable/repairable damage limits. For example, when detected damage reduces the residual load-carrying capability below the required ultimate load level, the component must be either repaired to restore that ultimate load capability or replaced. Replacement is mandatory only if a substantiated repair cannot restore the ultimate strength, or if the damaged structural member is short such that the repair of that member is impractical [22–24]. Extensive structural degradation, such as the spar damage and bird strikes illustrated in Fig. 1d and g, may therefore require replacement when no approved repair can restore the required ultimate-load capability to the necessary safety margins. Conversely, for non-extensive damage, repair may be applied when substantiated procedures exist and residual strength remains acceptable. Damage that remains below the Allowable Damage Limit (ADL) (e.g., Fig. 1c and h) may be left in service under a defined inspection interval without immediate intervention. However, for damage that exceeds the ADL but remains within a restorable regime, structural repairs are implemented to restore static strength, stiffness, and fatigue capability to the required design margins. If the residual-strength margin cannot satisfy the original design load cases with the prescribed safety factor, or if the damage size introduces unmanageable uncertainty during inspection, replacement remains mandatory to ensure structural integrity [25,26].

Polymeric composite repairs are broadly classified into three categories according to the severity and extent of damage to (i) cosmetic, (ii) temporary, and (iii) structural repairs [27]. Cosmetic repairs (Fig. 2a)

are applied when damage is superficial and does not compromise the structural integrity of the component, such as scratches or surface microcracks. Their purpose is to restore the aerodynamic contour and provide environmental protection (e.g., moisture sealing), thereby preventing further degradation. However, cosmetic repairs do not reinstate the primary load path or recover the original mechanical properties of the structure, since underlying defects, e.g., broken fibers, delamination, persist [28]. Temporary repairs are implemented to stabilize localized damage that does not immediately threaten structural integrity but may propagate under cyclic loading or environmental exposure. These techniques generally involve the application of an external patch or doubler (see Fig. 2b), often with minimal surface preparation, to arrest damage progression, introduce additional load paths, and enable safe operation until permanent repair can be conducted. External doublers may be attached to one or both sides of the repair, depending on factors such as accessibility and required structural performance. Single-sided repairs are often preferred due to practical accessibility. However, they induce out-of-plane bending because the neutral axis shifts under loading [29]. Numerical and experimental studies indicate that double-sided doublers are more efficient because they eliminate the induced bending effect, produce a greater reduction in the stress intensity factor at the crack tip, and significantly reduce the risk of premature buckling under compressive loading [30–32]. Depending on operational requirements, the damaged region may be removed or retained, and filler materials, often referred to as plugs, may be used to restore geometry and improve mechanical properties such as impact resistance [33–35]. In practice, external doublers are generally designed with simple geometries, such as rectangular, square, or circular configurations. However, numerical optimization studies have proposed alternative configurations, including X-shaped and butterfly-shaped patches, to improve repair efficiency. These studies demonstrate that such non-standard geometries can reduce material usage and structural weight, while maintaining load transfer capability and overall mechanical performance comparable to conventional square patches, with reported material savings of up to 4% [36]. Other optimization techniques include a modal-based shape optimization method that uses the first natural frequency as the design criterion for patch repairs. This approach determines the minimum dimensions of rectangular patches required to recover the mechanical response while balancing stiffness and inertia [37]. Recent advances have also introduced promising

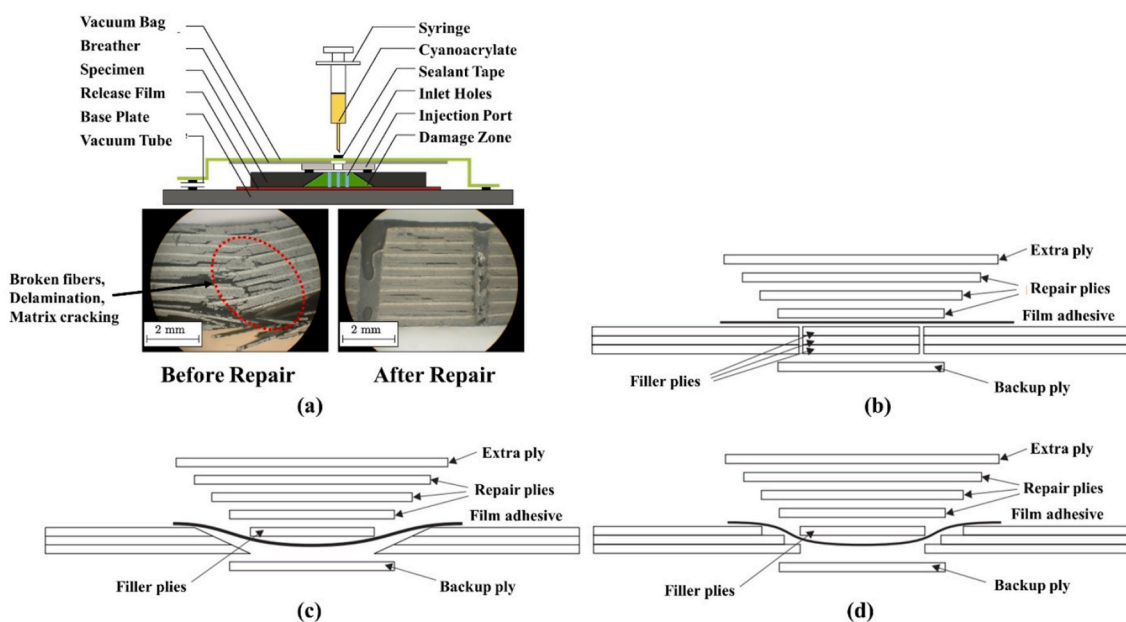


Fig. 2. Bonded repair configurations: (a) cosmetic repair, (b) external/doubler repair, (c) scarf repair, and (d) stepped-lap repair. Image sources: (a) adapted from Ref. [28], (b-d) taken from Ref. [45].

techniques for manufacturing patches in thermoplastic composites [38–41]. For example, in-situ automated repair processes using 3D printing technology can create bespoke continuous carbon fiber patches that are directly printed into recesses representing the damaged regions, or fabricate patches that are subsequently adhesively bonded to the substrate [38]. Other techniques include a “reverse modelling” approach, which utilizes digital reconstruction of damaged areas via light-scanning methods to generate CAD models of repair patches with high geometric compatibility to the substrate. This process is followed by bonding the fabricated patch using high-frequency ultrasonic welding at the interface [39]. In addition, 3D printing enables fiber steering within the patches, which allows reinforcement to be aligned with the principal stress directions and load paths to accommodate anisotropic stress and load distributions [40].

On the other hand, structural repairs are required when damage reduces the residual load-carrying capability of the structure such that compliance with the applicable ultimate load requirements can no longer be demonstrated. [42]. Such repairs are intended to restore structural strength, re-establish the primary load path, and maintain the required aerodynamic performance. This is typically achieved through an extensive procedure involving material removal of the damaged zone, followed by the installation of a tailored replacement patch to restore the properties of the compromised component. [43]. Depending on their method of fabrication and integration, such repair patches are generally classified into two main categories: soft and hard. Soft patches involve laying up plies in situ into the machined cavity and co-curing them with the parent laminate. Hard patches are pre-manufactured composite laminates fabricated in a mold under controlled conditions and bonded into the cavity using a film adhesive (secondary bonding). The most common structural repair techniques are scarf and stepped-lap repairs [44,45]. Scarf repairs (Fig. 2c) involve machining the damaged area to a continuous taper in the parent laminate and inserting either a hard or soft patch into the cavity. This method provides a smooth transition between patch and parent, reducing stress concentrations and promoting enhanced load transfer, which results in effective strength restoration [46]. Scarf repairs are among the most complex bonded repair geometries to execute. They require precise machining to achieve the specified taper angle, and meticulous control of adhesive application. The quality of the bond is highly sensitive to variations in bond-line thickness, as any non-uniformity can substantially increase local shear and peel stresses at the interfaces, raising the risk of premature adhesive or laminate failure [47]. Stepped-lap repairs (Fig. 2d) remove damaged material in discrete steps, thereby forming a series of overlapping single-lap joints through which load is transferred across multiple adhesive layers. This configuration reduces load eccentricity and distributes stresses over several load paths, so that each step carries only a fraction of the total load, thereby limiting localized bending moments and improving structural stability [35]. A key mechanical advantage over scarf geometry is the lower sensitivity of stress peaks in stepped-lap joints to variations in adhesive thickness, which makes them comparatively more tolerant to bond-line inconsistencies during manufacturing [47]. However, stepped-lap repairs are generally less robust than scarf repairs because the geometric discontinuities at step edges introduce stress concentrations that can reduce long-term durability and promote premature failure [48,49]. Nevertheless, careful design of stepped-lap joints can achieve performance comparable to scarf repairs. One such example of good design is increasing the number of steps such that it approaches the ply count. This increases the number of plies participating in load transfer within the repair, thus increasing the performance of the repaired joint [46,50,51]. In addition, numerical investigations suggest that peak interfacial stresses and debonding initiation can be mitigated through functionally graded adhesives (FGA), which vary mechanical properties along the bond-line. This can be achieved by combining stiff, brittle and ductile compliant adhesives to optimize the balance between joint stiffness and fracture resistance. Such a grading strategy can reduce stiffness mismatches and strain

incompatibilities, thereby delaying failure onset and supporting a more progressive damage evolution [52]. In practice, repairs are commonly carried out using the soft-patch method. This means even when cavities are tapered, ply edges usually form step drop-offs that resemble stepped-lap joints, making stepped-lap repairs more prevalent in field applications [53].

Both scarf and step lap repairs typically remove the damaged material in a circular or rounded rectangular outline and restore the laminate with a scarf or step lap patch with a constant taper or step-lap ratio through the laminate thickness. Uniform step ratios on the order of 1:30 are commonly applied when repairing aeronautical structures irrespective of ply orientation to ensure conservative, certification-compliant load transfer [44,54]. The selection of the taper angle or step ratio can also influence the failure mechanisms that develop within the bonded repair [55]. In this context, steep taper angles generally promote purely cohesive adhesive failure. In contrast, shallower taper angles below 3° tend to induce a complex mixed-mode failure mechanism that combines cohesive adhesive failure with delamination of the parent laminate, which is therefore considered more beneficial in terms of structural repair performance [56–58]. However, the certification-driven preference for uniform and conservative step or scarf ratios across the entire repair geometry commonly requires removal of substantial undamaged parent material. This increases repair size, material waste, and aircraft downtime, the latter costing operators between \$100,000 and \$200,000 per day [59]. Recent investigations demonstrate that this requirement for a uniform repair geometry is mechanically suboptimal, as evidence suggests that a nominal overlapping length is only strictly necessary in the direction of the reinforcement fibers for efficient stress transfer. This “fiber-oriented” approach has been validated through several optimized designs. For example, Piece-wise Linear (PWL) scarf designs [60] in which load-bearing 0° plies are assigned shallow tapers (e.g., 1:30) while off-axis plies ($\pm 45^\circ$, 90°) are machined with steeper tapers (e.g., 1:2). The results reported a 75% tensile strength restoration while reducing the repair area by 60% compared to a conventional straight scarf. Furthermore, the Variable-Length Stepped Scarf (VLSS), where shorter overlaps are assigned for off-axis plies and longer overlaps are only in areas where strictly necessary for stress transfer in the direction of the reinforcement fibers. This has been shown to restore 95% of original stiffness and 64% of static strength while maintaining a repair size 39% smaller than industrial practice [61]. Beyond taper tailoring, bio-inspired suture interfaces represent a distinct strategy that reduces the required repair size and enhances mechanical performance. By introducing interdigitated, mechanically interlocking geometries inspired by the interlocking architecture of the ironclad beetle's elytra. The proposed interfaces can promote progressive load transfer through combined adhesive bonding and geometric engagement [62]. The mechanism was shown to mitigate peak interfacial shear stresses, delay crack initiation, and enable distributed energy dissipation through crack deflection and frictional sliding. The structural repairs in this case reported tensile and bending repair efficiencies of 81.1% and 80.7%, respectively, enabling more effective restoration of primary structural components. The improved interfacial efficiency allows a smaller bonded area to carry equal or greater loads than conventional smooth interfaces, while enhancing mechanical performance under both tensile and bending loading.

Structural repair of FRPs is mainly performed using two established techniques: mechanical fastening and adhesive bonding. Mechanical fastening, which employs rivets, bolts, or screws to secure a patch to the parent structure, remains widely practiced due to its procedural simplicity and long-standing certification history [63]. However, the introduction of fastener holes induces localized stress concentrations that promote crack initiation and accelerate damage propagation [40]. This often results in a reduction in the mechanical integrity and fatigue life of the repaired region [64–66]. Furthermore, installing fasteners into composite structures can aggravate damage and pre-existing

delamination due to high axial forces [67,68].

By contrast, adhesive bonding eliminates the need for fastener holes and promotes a more uniform stress distribution across the repair interface, thereby improving load transfer efficiency and fatigue resistance. However, unlike mechanical assembly repairs, adhesively bonded repairs cannot transfer 100% of the load in unidirectional FRP laminates. This limitation in load transfer can be significantly mitigated in multidirectional laminates, where off-axis plies redistribute stresses, reduce local peel and shear concentrations at the bond-line, and improve damage tolerance [69–71]. Furthermore, adhesive bonding enables joining dissimilar materials (e.g., aluminum with steel or thermoplastic with thermosets) and maintains surface continuity, thereby preserving aerodynamic efficiency and ensuring conformity with the original design specifications [72–74].

Owing to these advantages, adhesive bonding has gained widespread adoption as a preferred approach for high-performance composite repairs [75]. Bonded structural repair process follows a standardized sequence of steps, as defined by regulatory authorities such as the Federal Aviation Administration (FAA) and Structural Repair Manuals (SRMs) provided by Original Equipment Manufacturers (OEMs) such as Airbus and Boeing [76,77]. The typical procedure consists of six main steps, as can be seen in Fig. 3. Nevertheless, the bonded repair process is often highly labor-intensive, difficult to automate, and heavily dependent on operator skill and consistency [39]. Carrying out repair operations in aerospace, wind energy, and marine sectors in on-site conditions is often challenging due to insufficient access to required infrastructure and tools, as well as constraints imposed by the operating environment. This limitation renders component disassembly impractical, thereby necessitating reliance on conventional repair methods [78–80]. Conventional machining (CM) techniques, such as milling, grinding, and drilling, often introduce a range of surface and subsurface defects in FRPs, such as fiber pull-out and matrix degradation. These defects arise primarily from excessive mechanical deformation and localized thermal damage, both of which result from the continuous contact between the cutting tool and the composite material, coupled with the poor thermal conductivity of FRPs [81,82]. Consequently, the mitigation and control of machining-induced defects represent a critical challenge in achieving reliable and repeatable bonded repairs. As will be discussed in Section 2, these challenges become particularly pronounced for components with irregular geometries or complex laminated layouts. This is because the

severity of machining damage strongly depends on fiber orientation, and the high cutting forces generated during CM interact with the anisotropic nature of composite materials. These interactions lead to non-uniform stress distributions and unstable material removal processes, thereby increasing the risk of secondary damage and ultimately resulting in repair rejection.

Surface preparation is a critical factor in joint performance, as inadequate or inconsistent treatment can substantially reduce adhesion strength and compromise both mechanical integrity and long-term durability [83]. Therefore, a series of preparatory steps is required to ensure that the surface is free from contaminants, residual moisture, and properly activated for subsequent bonding [84]. This renders surface preparation not only technically demanding but also highly time-consuming, establishing it as one of the most critical stages in the bonded repair process [85,86]. Similarly, the adhesive curing process exerts a significant influence on bond quality. The porosity level and bond-line thickness of the adhesive depend strongly on the curing method employed. For example, autoclave curing provides precise control over temperature, pressure, and vacuum conditions, enabling high-quality manufacturing with minimal porosity formation. Conversely, in in-situ repair scenarios, curing typically relies on portable heat blankets or infrared lamps, which often result in non-uniform bond-line temperatures and localized overheating [87]. Such localized thermal variations frequently lead to inadequate pressure application, producing porosity levels of up to 10% within the adhesive layer and between plies in soft-patch repairs, both of which significantly degrade the mechanical performance of the bonded structure [88]. Furthermore, microscale defects within the adhesive layer, such as air bubbles (porosity) and variation in adhesive thickness, are commonly observed even under optimal curing conditions. These defects act as local stress concentrators, which disturb the nominal stress field and compromise load transfer across the bond-line. Their impact on repair performance is particularly significant when they are located near overlap ends or interfaces, where peak stresses typically occur. In addition, empirical and numerical studies demonstrate that even moderate defect densities can accelerate crack initiation and propagation under mechanical and environmental loading, undermining joint performance and long-term reliability [89,90]. Adhesive bonding defects can further interact with composite damage modes. For example, voids in the adhesive can shift a fracture from the bonded interface into the adhesive layer, and

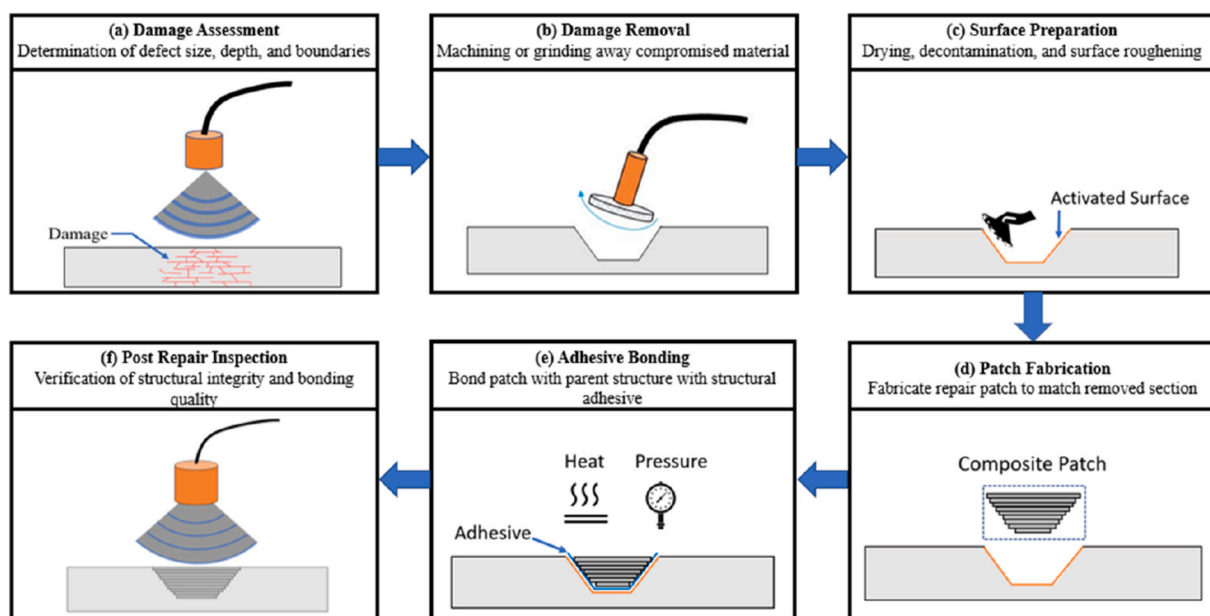


Fig. 3. Sequential stages involved in composite bonded repair process: (a) damage assessment, (b) damage removal, (c) surface preparation, (d) patch fabrication, (e) adhesive bonding, and (f) post-repair inspection.

conversely, an interfacial crack can drive delamination into the composite plies [91].

Nevertheless, the main challenge is not confined to in-situ repair itself. While in-situ repairs typically rely on manual operations due to the absence of advanced manufacturing infrastructure, it is important to

note that the use of advanced technologies does not necessarily eliminate repair-related challenges. This is demonstrated in the micrographic study by Whittingham et al. [92], who compared soft-patch, molded hard-patch, and machined hard-patch repairs in bonded carbon/epoxy laminates produced using different advanced fabrication methods. The

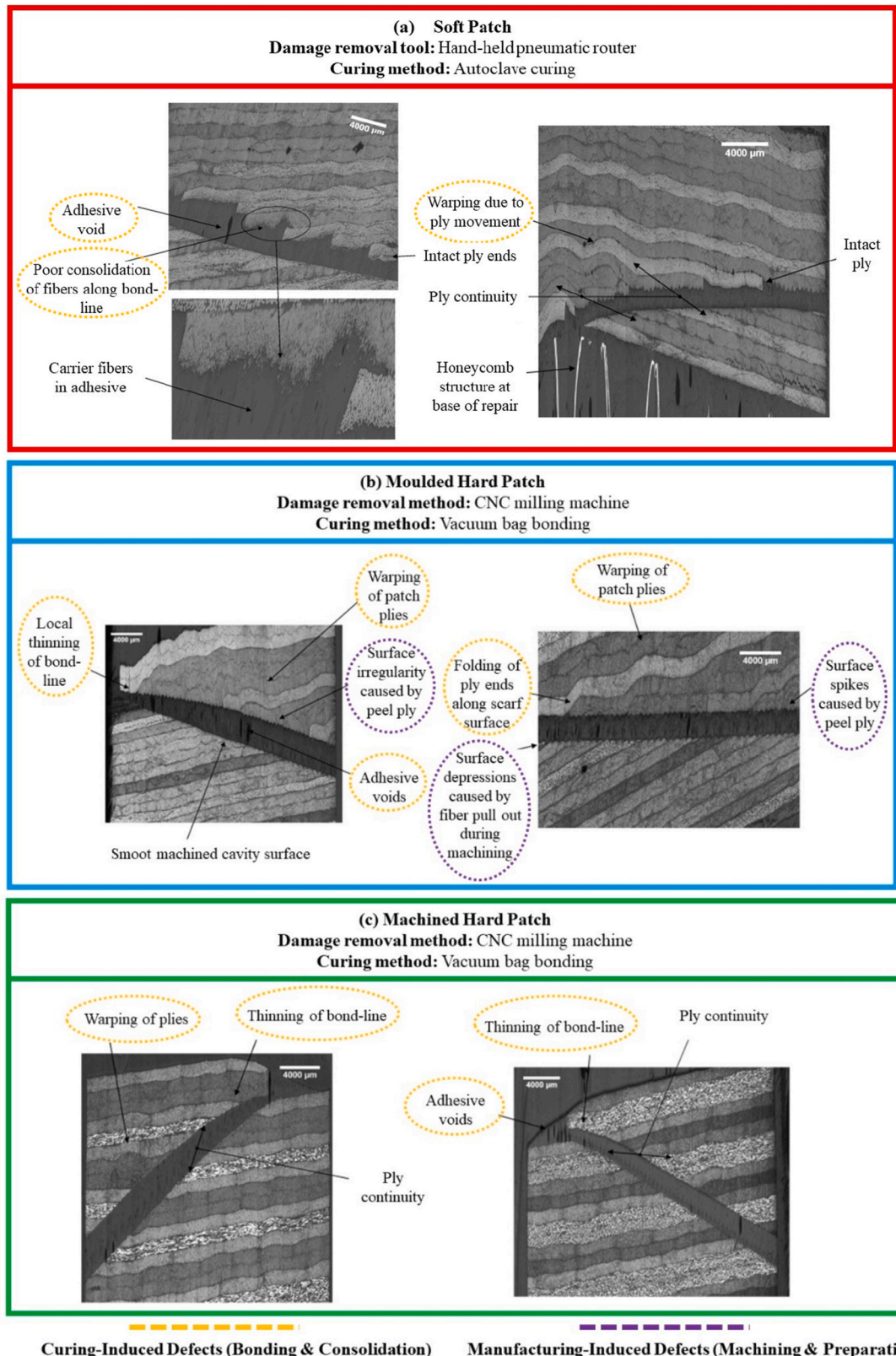


Fig. 4. Composite bonded repair defects observed in: (a) soft patch, (b) molded hard patch, and (c) machined hard patch (adapted from Ref. [92]).

soft-patch approach (Fig. 4a), although cured in an autoclave, exhibited poor fiber consolidation at the bond interface and notable ply distortion caused by fiber movement during curing, which resulted in considerable variation in bond-line thickness. In contrast, the hard-patch repairs (molded and machined, Fig. 4b and c), produced using a CNC milling machine, displayed higher bond-line porosity levels. This is mainly due to non-autoclave curing and surface imperfections such as adhesive thinning and fiber pull-out-induced depressions caused by the machining process. However, it exhibits lower ply distortion and nearly half the bond-line thickness variation than the soft-patch repairs. This improvement is primarily attributed to the superior geometric precision of CNC-machined cavities compared to a manual pneumatic grinding tool. The observed defects may originate either during the curing process or during machining and patch preparation. However, the effect of these repair-induced defects on the overall structural integrity of bonded joints remains insufficiently understood. This knowledge gap arises largely from the difficulty of producing representative repair samples with consistent and quantifiable defect characteristics [93]. Consequently, the current assessment of repair quality relies predominantly on Non-Destructive Testing (NDT) techniques [94]. However, no single NDT method currently available can identify all defect types within composite repairs, nor can any provide a fully reliable evaluation of the final bond quality [76,95,96]. Techniques such as ultrasonic inspection, infrared thermography, and X-ray radiography often struggle to detect small-scale defects or weak adhesive interfaces due to the absence of fundamental signals to detect these defects.

One such example is kissing bonds, which refer to a condition where surfaces are in apparent contact but are not properly bonded at the molecular level, which can influence the repair behavior and long-term stability of repairs [97–99]. Moreover, NDT methods cannot directly quantify bond strength, thereby necessitating destructive testing for verification, which is an impractical approach in actual repair applications [100,101]. A further concern is that early-stage damage, such as internal delamination and resin cracks, may close when loads are removed, leaving no visible signs during NDT inspection, yet potentially progressing rapidly upon return to service and increasing the risk of catastrophic failure [102]. Additionally, during service, environmental exposure (aging, temperature, humidity, UV radiation) can significantly affect the long-term durability of bonded repairs. Bonded joints suffer substantial strength loss in humid conditions because adhesives absorb water, which causes plasticization and swelling, promotes micro-void formation, and weakens the fiber-matrix interface [103–105]. Additionally, moisture uptake in the adhesive can reduce its Young's modulus and tensile strength, thereby decreasing repair efficiency [106]. Elevated temperatures further modify this response by softening the composite matrix, which results in a pronounced reduction in inter-laminar strength [107]. Joint strength degradation is most severe when moisture uptake and thermal effects act simultaneously and synergistically, resulting in greater bond degradation than either factor acting independently [108]. Furthermore, ultraviolet irradiation can facilitate moisture ingress, concentrate stresses at the adhesive interface, and embrittle the adhesive. The simultaneous presence of two or more environmental factors can cause a shift in failure mode from cohesive failure within the adhesive to interfacial debonding. This change drastically reduces fracture energy and compromises the structural integrity of the repair [109].

Owing to the aforementioned limitations, certification bodies restrict adhesive bonding repairs primarily to non-primary structural components [110,111]. In this context, Structural Health Monitoring (SHM) has emerged as a promising complementary approach. By embedding high-fidelity sensors within the repair, SHM systems enable continuous monitoring of the structure's response throughout its service life, allowing defective repairs to be identified and addressed proactively, thereby enhancing reliability and preventing sudden or catastrophic failures in bonded structures [112]. Addressing the challenges of machining, surface preparation, and post-repair quality assurance

requires an in-depth review of existing literature to identify the knowledge gaps regarding material removal, surface preparation, and SHM. In this regard, several review papers have summarized the current state of composite bonded repairs, as summarized in Table 1.

Table 1
Summary of existing review literature on composite bonded repairs.

Author(s)	Review themes
Katnam et al. (2013) [95]	Review of the challenges and opportunities for structural bonded repair in aircraft composites, covering damage assessment (NDT), material removal, surface preparation, patch types (hard/soft), structural design/analysis, durability, monitoring, and automation.
Baker et al. (2015) [113]	Review of certification challenges for bonded repairs of primary composite aircraft structures, focusing on long-term bond durability and the lack of certification-accepted generic design tolerances.
Niedernhuber et al. (2016) [114]	Review of fiber-oriented geometries for Carbon Fiber Reinforced Polymer (CFRP) stepped joints using mechanical and Finite Element (FE) analysis.
Budhe et al. (2018) [115]	Review on the environmental durability of adhesively bonded composite repairs in aerospace, thoroughly examining the individual and combined (hygrothermal) effects of moisture and temperature degradation on composites, adhesives, and bonded joints, including Finite Element Methods for prediction.
Molent et al. (2020) [116]	Review of the existing composite damage growth data under fatigue (primarily aerospace carbon/epoxy bonded joints) to prove that damage progression is systematic and predictable. Concludes that growth is a predictable function of simple metrics retrieved via field NDT, supporting a transition to a slow-growth design basis.
Zhou et al. (2021) [117]	Focuses on methods to enhance composite patch repair performance, covering optimization (geometry, dimensions, hybridization), effects of adhesive properties, improved repair methods (e.g., crack stop/hybrid), and the application of NDT (Acoustic Emission (AE), Digital Image Correlation (DIC), Infrared Thermography (IRT), micro-CT) for damage monitoring and evaluation.
Yudhanto et al. (2021) [118]	Review of the surface preparation strategies for secondary bonded thermoset composites. Analyzes how treatments (sanding, plasma, laser) activate adhesion mechanisms (mechanical interlocking, chemical bonding), modifying surface characteristics (roughness, energy) and influencing joint performance (strength, fracture toughness).
Orsatelli et al. (2023) [53]	Review of bonded flush repairs (scarf/stepped) for aerospace composites, synthesizing static failure mode data and analyzing modeling strategies (analytical, FE, Cohesive Zone Modelling). Focuses on optimization, reliability, durability, damage tolerance, fatigue, and impact behavior prediction.
Olhan et al. (2025) [119]	Focuses on the repair technologies for automotive structural polymeric composites. Topics include NDT damage assessment (e.g., BVID), composite machining, surface preparation, scarfing/patching/bonding, resin injection repair, and automation strategies.
Zhang et al. (2025) [120]	Presents a technology roadmap for Composite Joining and Repair (CJAR), focused primarily on aerospace CFRP. Summarizes current and future milestones across six areas: NDT, materials, processes, computational tools, automation, and standards/regulatory issues.
Ghafafian et al. (2025) [11]	Provides a multi-industry comparison of composite repair methods across marine, wind, automotive, and aerospace sectors. Highlights commonalities, contrasts distinct approaches, reviews ongoing research, and identifies opportunities to boost efficiency via new materials and automation.
Şen (2025) [121]	Provides a review on composite patch repair technologies for damaged metallic and composite structures. Synthesizes materials, patch configurations, analytical/FE modeling strategies, mechanical performance (SIF reduction, fatigue), inspection methods, and emerging trends across multiple industrial sectors.

Table 2

Summary of CM research on composite materials.

Repair implications	Uncut fibers or fiber burrs can cause irregular bond surfaces, poor wetting and increased rework/rejection.	Tool wear increases the amount of uncut fibers and extends the delamination near the free edge of the machined zone, complicating the alignment of the repair patch on the parent structure for bonding.	Angle-dependent damage implies that repair machining must either avoid the critical angular sectors or adjust tool kinematics and material (e.g., PCD with optimized feed) to minimize cavity formation. Otherwise, surface roughness (R_a) may reach 10–13 μm , resulting in a cratered topography that compromises adhesive contact and increases porosity at the substrate-adhesive interface, potentially reducing fatigue endurance.	Worn cutting tool nose radius favors higher machining temperatures and crater volumes. This increases subsurface damage which can seriously undermine bond integrity.	Dry grinding favors the formation of the HAZ (temperatures reach $\sim 350^\circ\text{C}$ for a depth of cut equal to 400 μm), leading to chemically and thermally altered/charred resin and degraded surface chemistry that prevents reliable adhesion. Wet grinding can reduce HAZ, but coolant complicates precise manual repairs (visibility/geometry control).	Conventional grinding heat (even at $\sim 100 \mu\text{m}$ of depth of cut) causes matrix smearing, fiber pull-out and delamination, which affects uniform bonding and lowers joint stiffness.	Subsurface damage depths (Δh) on the order of 100 μm , can cause significant reduction under tensile and compressive strengths. In addition, visually small surface defects can imply deep damage requiring removal beyond superficial finishing, increasing material removal and risk of out-of-tolerance repairs.
Key findings	Tool edge radius (wear) is a major factor: small r_n (sharp) $\rightarrow$ clean cut; large r_n $\rightarrow$ pronounced delamination and fiber protrusion. Critical angle ranges for delamination generation and propagation are identified.	Higher cutting forces and tool wear correlate with larger delamination depth and propagation; delamination depends strongly on fiber cutting angle and tool condition.	Surface cavities are highest at 45° – 70° , lower forces in cavity zones produce cavities and uncut fibers; higher forces outside cavities produce more severe subsurface damage.	Higher feed rates increase the cutting forces, while higher cutting speeds reduce them for a new tool (thermal softening) but high speeds accelerate wear, which then increases forces and damage later. Tool wear strongly correlates with force increase and roughness.	Dry grinding at larger depths forms HAL (thermal alteration at $\sim 350^\circ\text{C}$) and severe surface deterioration; wet grinding prevents the highest HAZ but can increase microdamage visibility	Continuous grinding heat can exceed T_g at modest depths (order 100 μm), producing resin smearing and delamination; ESG (intermittent grinding) reduces cumulative heat vs conventional smooth grinding.	Feed dominates R_a ($\approx 65\%$ contribution); cutting-edge radius dominates void fraction and Δh ($\approx 55\%$ contribution); down-milling raises void fraction but up-milling yields greater Δh in some cases; Δh strongly correlates with strength loss.
Damage modes	Fiber overhangs, Type I–III delamination modes, uncut fibers, and fracture of top layers	Top-layer delamination, uncut/protruding fibers, fiber overhangs; delamination propagation with engagement history	Fiber-matrix debonding, compression-induced fiber fracture, bending fracture, shear fracture; cavities in 0° – 90° region	Craters, uncut fibers, resin smearing, subsurface damage increasing with wear and feed	Heat-affected layers: (1) near T_g ($\sim 109^\circ\text{C}$) and (2) thermal alteration near $\sim 350^\circ\text{C}$; matrix loss, resin smearing, fiber detachment at high temps	Thermally driven damage (smearing) in CSG when T_g exceeded; ESG lowers heat accumulation and force peaks, but can create scallop control issues if parameters are not optimized	Surface voids/void fraction, matrix smearing, fiber deflection, subsurface affected depth Δh .
Measured responses	Optical/3D topography, SEM, delamination factor, damage depth	3D edge/topography, tool wear mapping, cutting force traces	Surface roughness (R_a/R_z), SEM damage mapping, and force components	IR surface temperature, 3D surface topography (S_a), crater volume, SEM, X-ray tomography	Surface roughness R_z (stylus), SEM, thermal simulation (HAZ depth), TG/DTA	Surface temperature, waviness/scallops, force components	R_a (multiple measurements), surface void fraction (image segmentation), depth of affected zone (Δh), 3D topography, SEM, quasi-static tensile/compressive tests
Maximum cutting forces	Active Force (Resultant) $\approx 538 \text{ N}$	Tangential (F_c) $\approx 200 \text{ N}$, Normal/Radial (F_{cn}) $\approx 350 \text{ N}$	Tangential (F_c) $\approx 15 \text{ N}$, Normal/Radial (F_{cn}) $\approx 25 \text{ N}$	Active Force (Resultant) $\approx 190 \text{ N}$	N/A	Tangential (F_c) $\approx 110 \text{ N}$, Normal/Radial (F_{cn}) $\approx 270 \text{ N}$	N/A
Tested parameters	feed, cutting speed, tool wear (controlled), edge radius	feed, cutting speed, tool geometry, tool wear (new vs worn), engagement angle	cutting speed, feed, depth, fiber angle sweep	feed, cutting speed, cutting distance	depth of cut Δ (40–400 μm), wheel speed, dry vs wet coolant	depth of cut (20–100 μm), wheel speed (e.g., 3000 rpm), feed (5 m/min typical), eccentricity (ESG)	Spindle speeds; feed; up- vs down-milling
Tool	Double-edged Polycrystalline diamond endmills	Carbide single-edged tool	Polycrystalline diamond cutter	Polycrystalline diamond cutter	Vitrified diamond wheel	Conventional and eccentric grinding wheel configurations; abrasive grains	Tungsten-carbide 2-flute endmill
Operation	Milling	CNC milling	Circular orthogonal milling	Trimming	Grinding (dry vs wet)	Conventional surface grinding, eccentric sleeve grinding	Side/edge milling
Source	Hintze et al., 2011 [136]	Voss et al., 2017 [134]	Wang et al., 2017 [135]	Nguyen-Dinh et al., 2019 [137]	Kodama et al., 2020 [142]	Handa & Sooraj, 2022 [143]	Qin et al., 2022 [139].

In addition, there are many reviews available on SHM of composite [112,122–128]. These past reviews focused on structural design and durability (including repair geometry and FEA), environmental and fatigue durability, and traditional surface preparation strategies and NDT. However, to the authors' knowledge, no prior work has examined the dual application of abrasive waterjet machining (AWJM) technology for both damage removal and surface preparation, nor has any review specifically focused on SHM applications within composite bonded repair systems. In this context, and in view of the issues discussed above, this review addresses the growing need for a more integrated

understanding of certification and health monitoring methodologies in bonded repair practice. Therefore, the main goals of this review are to: (1) evaluate the limitations of conventional machining techniques and trace the evolution of damage-removal strategies toward non-conventional approaches, with special attention to AWJM technology and its ability to reduce machining-induced defects and integrate damage removal and surface preparation into a single, time-saving operation; and (2) evaluate the incorporation of SHM techniques into adhesively bonded repairs, focusing on three sensor classes, namely fiber-optic sensors (FOS), piezoelectric transducers (PZT), and

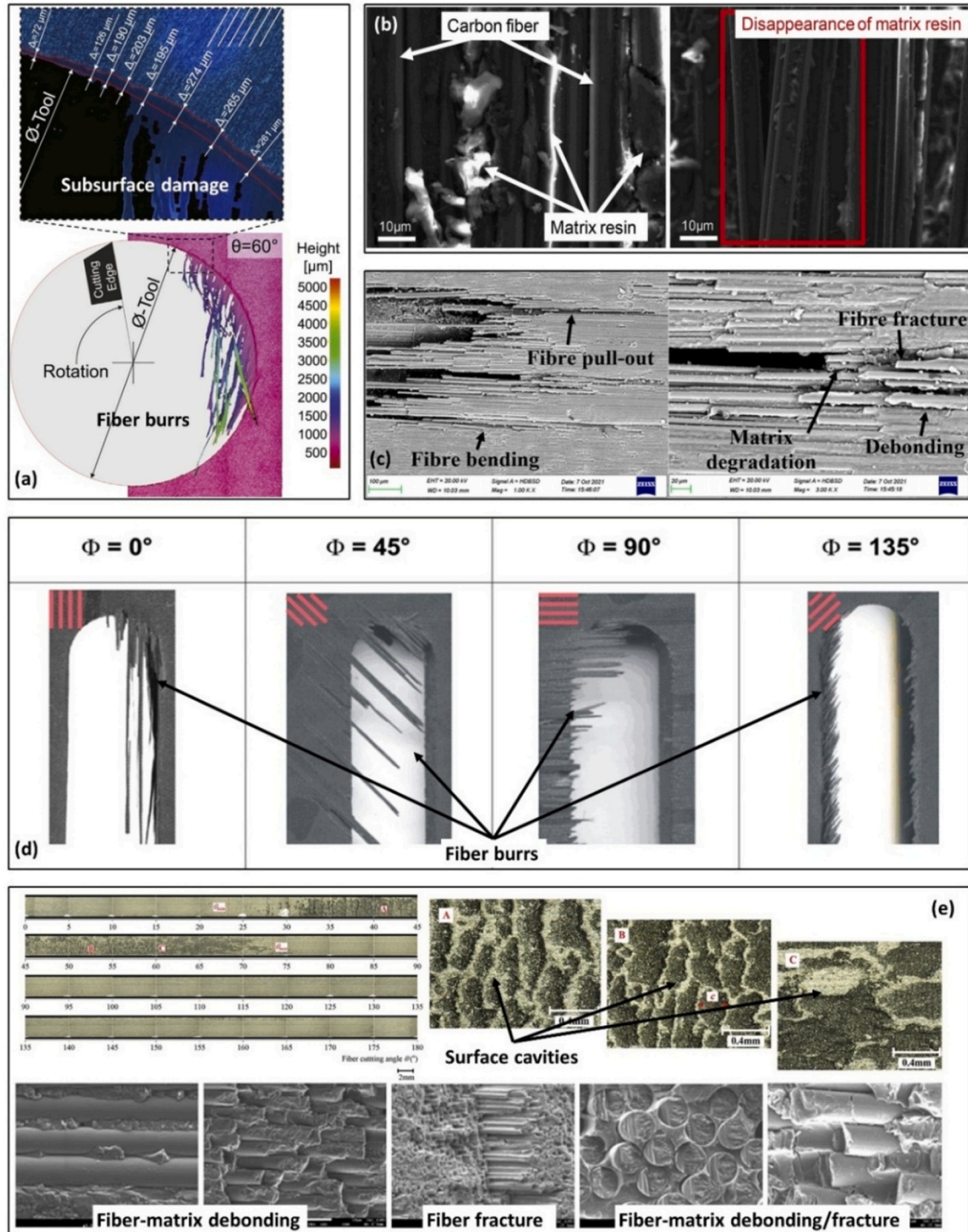


Fig. 5. Typical CM damage modes during (a) CNC milling [134], (b) dry grinding [142], (c) surface grinding [143], (d) slot milling [136], and (e) orthogonal milling [135].

piezoresistive sensors (PZR). In the end, this analysis offers a comprehensive viewpoint on how these new methods can improve the certification and reliability of bonded repairs in structural applications.

2. Damage removal methods

2.1. Conventional machining (CM)

Machining-induced damage can drastically influence the strength and fatigue performance of FRP components and is responsible for approximately 60% of part rejects prior to their assembly [129]. The most common surface and subsurface defects during CM include delamination, fiber pull-out or protrusion, matrix smearing, matrix burnout, and cavity formation [130,131]. These defects act as local stress concentrators that reduce endurance limit and degrade stiffness and strength, directly compromising repairability and structural longevity [132,133]. Over the years, extensive research investigated the effects of CM process parameters on surface and subsurface defect formation, as summarized in Table 2. The formation of these defects is not random but rather due to the interaction between material properties and cutting mechanisms. In particular, the angle between the cutting direction and the fiber (the fiber-cutting angle) determines whether the tool severs, bends or peels fibers; this angle dependence controls both the partitioning of tangential and radial forces and the resulting surface morphology, so that *against-fiber* sectors (0° – 90°) can produce low cutting forces but result in highly damaging cavity morphologies, whereas cutting *along-fiber* direction generates larger forces, often deeper, subsurface damage (Fig. 5a) [134,135]. Tool geometry and progressive wear further modulate these angle-dependent effects. As edges blunt the contact area and friction increases, the cutting action shifts from pure shearing to bending and tearing, which increases delamination and leaves uncut or protruding fibers, effects that are particularly pronounced when machining near 90° ply orientations (Fig. 5d) [134,136]. Empirically, polycrystalline diamond (PCD) tool nose radii have been observed to grow from $\approx 3\text{ }\mu\text{m}$ (new) to ≈ 7 – $11\text{ }\mu\text{m}$ with use, a change that correlates with higher surface temperatures (up to $\sim 127^{\circ}\text{C}$) and increased internal damage volumes in trimming tests [137]. Correspondingly, circular and orthogonal milling studies document angular bands in which cavity and crater morphologies dominate (typical cavity windows $\approx 24^{\circ}$ – 72° with peak severity $\approx 45^{\circ}$ – 70°), producing surface roughness in the order of 10 – $13\text{ }\mu\text{m}$ and cavity depths and widths that exceed accepted aerospace bonding tolerances (Fig. 5e) [135,138]. These mechanical effects interact nonlinearly with process parameters. For example, increasing cutting speed while reducing feed and limiting cutting distance can lower instantaneous cutting forces and improve the near-surface finish at the start of life, but high speeds accelerate abrasive wear so that, over realistic cutting distances, crater volumes, roughness, and subsurface damage ultimately increase [137]. Indeed, feed was shown to be the dominant cutting parameter affecting surface roughness, while cutting-edge radius is mainly responsible for the subsurface void fraction and affected depth. When this subsurface damage was increased from $\approx 46\text{ }\mu\text{m}$ to $\approx 306\text{ }\mu\text{m}$, tensile strength loss rose from $\approx 5.8\%$ to $\approx 24.7\%$ and compressive strength loss from $\approx 12.8\%$ to $\approx 38.8\%$, demonstrating that visually small surface defects can hide damage that substantially reduces structural capacity and therefore requires deeper removal [139]. In addition, thermal degradation occurs, where frictional heating and prolonged contact with worn edges produce heat-affected zones (HAZs) [140,141]. Kodama et al. [142] identified two distinct HAZs, a near- T_g layer ($\sim 109^{\circ}\text{C}$) and a deeper, thermally altered layer near decomposition ($\sim 350^{\circ}\text{C}$) forming at depths up to $400\text{ }\mu\text{m}$ during dry grinding (Fig. 5b). Wet grinding prevents these extreme temperatures but introduces coolant-related contamination and limited visibility for precise manual scarfing. Handa and Sooraj [143] reported similar findings, observing that conventional surface grinding could lead to continuous heat accumulation and temperature increases exceeding the glass transition temperature in CFRPs at cutting depths

around $100\text{ }\mu\text{m}$. This resulted in extensive resin smearing, fiber pull-out, and severe delamination zones (Fig. 5c).

The results demonstrate that CM possesses limited capability to meet the conflicting requirements of subsurface damage removal and high-integrity surface formation for bond repairs. The formation of craters, characterized by matrix degradation and broken fibers (Fig. 5c), during the cutting process results in excessive surface roughness. Although this may enhance wetting and facilitate the penetration of adhesive into cavities during curing, a high crater density can lead to a drastic reduction in mechanical properties [144,145]. Furthermore, as cutting tool wear progresses, the risk of subsurface damage, HAZs, and dimensional errors increases (e.g. fiber burrs in Fig. 5d) [146–148]. Such dimensional inaccuracies limit precise repair geometries, whether step-lap or scarf. In step-lap repairs, for example, these errors can result in epoxy-rich or porosity-rich zones between the patch edges and the step-lap contours after curing. Similarly, in scarf repairs, dimensional errors may lead to significant variations in bond-line thickness. Consequently, achieving the required dimensional precision while avoiding additional fiber or matrix damage can be challenging using the CM process, even with highly experienced operators. In fact, several studies have reported that machining-induced damage is common, even under optimal machining conditions and with the optimal design of the cutting tool [137,149,150].

The formation of HAZs further complicates this issue. The development of the HAZs can, on the one hand, cause degradation of the fiber/matrix interface in the laminate and, on the other hand, lead to chemical degradation of the substrate. In cases of substrate degradation, additional material removal is required to prevent unreliable bonding of the film adhesive [151,152]. Furthermore, based on the work of Kodama et al. [142], the subsurface damage depth induced by the HAZ during conventional grinding is reported to be on the order of $100\text{ }\mu\text{m}$ or more. In this situation, interaction with geometric tolerances requires material removal beyond superficial finishing, which directly increases the risk of out-of-tolerance repairs. It is important to note that a HAZ of approximately $200\text{ }\mu\text{m}$ corresponds to the typical ply thickness of the laminate. In this case, removing plies to eliminate the HAZ disrupts the structural balance of the laminate, introducing unpredictable deformations that make achieving the required dimensional precision nearly impossible. In addition to these structural challenges, airborne carbon fiber or matrix dust generated during conventional machining, such as epoxy particles, poses health and contamination risks. These particles can compromise bond surfaces and operator safety, further motivating the use of alternative non-conventional machining techniques for composite repair [153].

2.2. Non-conventional machining - abrasive water jet machining (AWJM)

To mitigate the defects associated with CM, various non-conventional machining technologies are evaluated by researchers. These include laser beam machining (LBM), electrical discharge machining (EDM) and abrasive waterjet machining (AWJM). LBM commonly induces significant thermal damage that it is incompatible with repair bonding [154], while EDM depends on material conductivity, limiting its usage for polymer composites [155]. Therefore, AWJM promises a suitable alternative for composite repair applications. Abrasive waterjet machining (AWJM) operates on the principle of using a high-velocity jet of water mixed with fine abrasive particles (e.g., garnet) to remove material through a combination of micro-cutting and erosion mechanisms [156]. AWJM overcomes several key limitations of CM such as: (i) AWJM-induced damage is far less dependent on the laminate's anisotropy and microstructure (e.g. fiber orientation), such that surface and subsurface integrity depend more on process parameters rather than on the laminate stacking sequence. (ii) because AWJM is a cold cutting process, it does not produce heat-affected zones (HAZs) and therefore does not cause thermal damage to the polymer matrix that can compromise mechanical performance and bonding quality - in the

case of bonded repairs [157,158].

(iii) The continuous water flow flushes away most of toxic carbon fiber debris, improving workplace cleanliness and operator safety. (iv) Since AWJM involves no direct contact between a cutting tool and the workpiece, tool wear is effectively negligible. Any measurable wear is limited to the nozzle (which focuses the abrasive jet) and the orifice (which forms the high-pressure water stream) and typically occurs only after hundreds of hours of operation at consistently high-pressure levels. As a result, AWJM offers a more economical and sustainable solution, eliminating the performance and quality issues commonly associated with tool wear [161–163], and (v) Removing a constant depth of cut in uneven surfaces can be easily achieved using AWJM process in comparison to CM. CM requires continuous change of the vertical distance between the cutting tool and the point of material removal to ensure constant depth of cut as illustrated in Fig. 6a and b [159]. In the present context depth control is defined as the ability to obtain ply-by-ply accuracy, that is, the selective removal of a single laminate ply while remaining within allowable depth tolerances that prevent damage to the subsequent ply interface. Notwithstanding these advantages, studies on drilling and milling with AWJM have shown multiple defect types such as striations, broken fibers, ridges/valleys, broken/bare fibers, embedded abrasive particles, fiber-matrix debonding, and micro/macro craters (Fig. 7) [144,160,164]. However, the practical question for repair is not whether AWJM induces damage in the structure, but whether that damage is controllable, predictable, and less severe than that induced using CM. From this standpoint, AWJM performance is largely governed by several parameters, including water pressure (WP), traverse speed (TS), stand-off distance (SoD), scan-step (SS), and abrasive flow rate (AFR). The optimization and control of these parameters directly influence material removal rates, surface quality, and defect generation [165]. Phapale et al. [166] found that increasing WP, SoD, or AFR increased delamination and exit hole size in woven CFRP drilling, although AFR had a relatively less pronounced role. However, using a backup plate was found to eliminate delamination even under parameters that typically induce serious damage. Akıncioğlu [167] reported that higher WP during drilling significantly reduced S_a , delamination, and kerf angle for aramid reinforced polymer (AFRP) by increasing the kinetic energy of abrasive particles. Small SoD improved cutting accuracy and minimized tapering, while a lower TS enhanced surface smoothness and reduced defects. WP was identified as the most influential parameter, contributing over 60% to machining quality. Hejjaji et al. [144] observed that higher WP during controlled depth milling of CFRP increased material removal rate (MRR), crater volume (C_v), arithmetic mean height (S_a), and waviness, resulting in damage such as fiber-matrix debonding and micro-craters. Conversely, higher TS was shown to reduce C_v and MRR but caused larger macro-craters. The presence of macro-craters was shown to reduce the tensile strength of the machined specimens by 30% compared to specimens characterized by the presence of micro-craters in the subsurface. Additionally, smaller SS was shown to improve material removal depth and overlap but increased surface waviness and damage, while larger steps reduced overlap but compromised machining uniformity. Although SoD had

minimal impact on MRR, closer distances increased damage patterns by significantly influencing the surface waviness. Sourd et al. [168] showed that, during controlled depth milling of 3D woven CFRP, lower TS increased C_v and damage, while higher TS reduced matrix erosion but promoted fiber-matrix debonding. High WP (>137 MPa) effectively flushed abrasive particles ($<1\%$ abrasive contamination) but increased crater formation and internal cracks. However, it is important to note that the SoD affects the spreading of the water-abrasive jet before it impacts the workpiece. Consequently, the jet diameter at the exit of the focusing tube may differ from the diameter when it reaches the material surface, resulting in variations in erosive behavior [169]. Indeed, Billingham et al. [170] suggests that the scan step should be adjusted so that the distance between consecutive jet passes is approximately equal to the jet diameter at the material surface. For a given experimental setup, this jet spread can be quantified by measuring the effective jet diameter at impact, for example using high-speed imaging [164].

These studies show that appropriate parameter selection enables effective control of the damage extent and surface morphology induced by AWJM. Although various types of defects can occur, the resulting damage is predominantly superficial, characterized by uniform surface roughness (craters and streaks) with minimal matrix smearing or delamination and only light subsurface damage, unlike CM, which has been shown to generate non-uniform, deeper subsurface defects. Interestingly, direct comparisons under quasi-static loading report similar ultimate tensile strengths (UTS) for AWJM and CM, indicating that the localized subsurface defects characteristic of CM and the surface characteristic of AWJM do not substantially propagate during monotonic loading. In fatigue, however, CM's deep, uneven defects act as severe stress concentrators that accelerate damage initiation and accumulation, reducing the endurance limit by roughly 10% relative to AWJM, as can be seen in Fig. 8. This is primarily attributed to AWJM being a cold erosive process that generates no matrix smearing and primarily confines damage to the surface layer, thus delaying crack growth and delivering superior fatigue performance under high cyclic stresses [171]. Although this 10% improvement in endurance limit was specifically observed for unidirectional and angle-ply laminates, its magnitude varies with the fiber architecture. For 2D woven fabric composites, such as five-harness (5HS) and eight-harness (8HS) satin carbon/epoxy, the endurance limits remain statistically identical between AWJ and CM, approximately 260 MPa and 355 MPa, respectively, due to the ability of interlaced yarns to effectively arrest early damage. Nevertheless, even in these woven systems, AWJM provides superior long-term durability. Evidence demonstrates that once a loading threshold of $\sim 60,000$ cycles is exceeded, conventional drilling induces up to 78% higher temperature rises and advanced stiffness loss compared to AWJM counterparts [172]. Similarly, in 3D interlock woven carbon fiber composites subjected to open-hole tensile fatigue, AWJM produces higher average lifetimes compared to conventional machining, with characteristic cycles to failure of approximately 106100 versus 98000, representing an approximately 8% improvement in fatigue life [173]. These results demonstrate that while the 10% improvement in endurance limit is most evident in architectures prone to drilling-induced delamination, AWJM

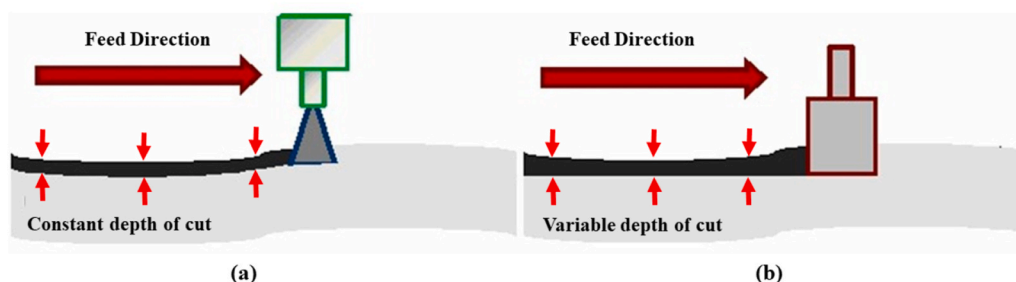


Fig. 6. Material removal on uneven surfaces using (a) AWJM, (b) CM (adapted from Ref. [159]).

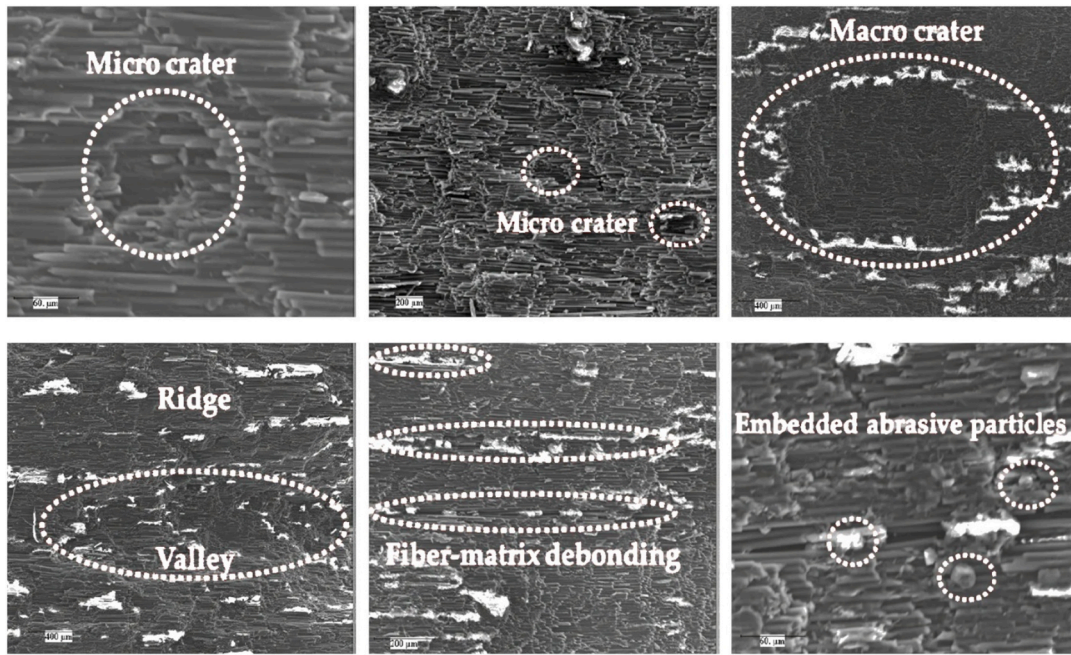


Fig. 7. Surface characteristics of CFRP following abrasive waterjet milling [160].

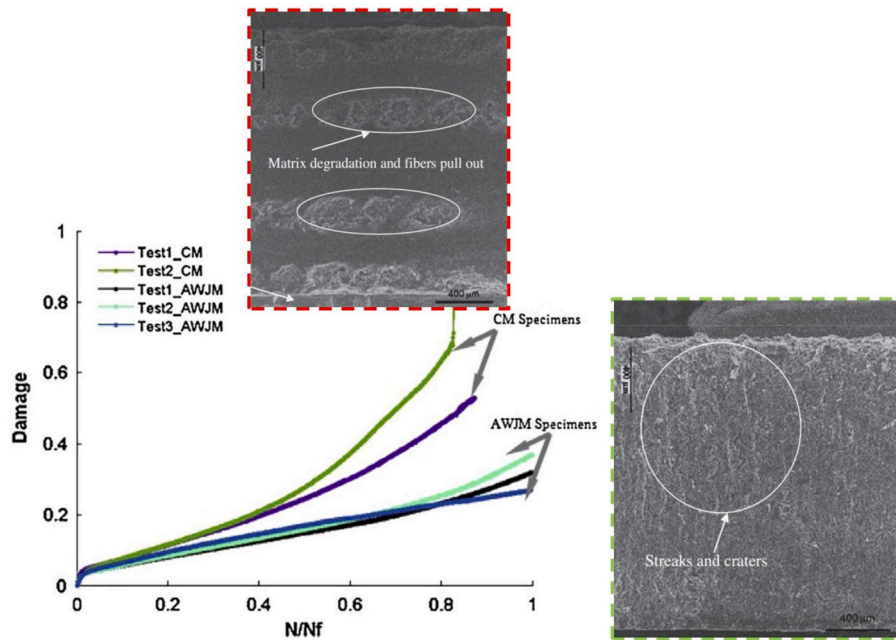


Fig. 8. Fatigue performance of CFRP machined by AWJM and conventional drilling process representing evolution damage evolution characteristics plotted against normalized fatigue life ratio N/N_f where N is the applied cycles and N_f is the total cycles of failure (adapted from Ref. [171]).

consistently enhances long-term performance across diverse woven systems by significantly delaying damage propagation.

Beyond improved damage control and better fatigue performance, AWJM also enables high-fidelity ply-by-ply milling because the method generates substantially lower cutting forces compared to CM methods. Hlaváč et al. [174] developed a force measurement device and found that the cutting forces during AWJM of 10-mm thick steel and copper plates were negligible (<10 N). Although the exact values depend on material type and thickness, the forces are expected to be lower for composite materials, particularly in controlled depth milling operations. On the other hand, studies reported in Table 2 show that cutting forces during CM can reach hundreds of Newtons depending on the depth of

cut and feed. In laminated composites with varying ply angles, larger machining forces produce greater coupled bending-torsion moments in non-symmetric and unbalanced stacking sequences, which in turn cause more out-of-plane deformation than that which occurs in symmetric, balanced layups [175]. Ply-by-ply milling typically disrupts local symmetry and balance. For identical fixturing and geometry, higher cutting forces therefore lead to substantially larger deflections, which may compromise ply-by-ply removal accuracy. This implies that AWJM will produce much smaller part deflections, making Δ SoD correspondingly small. While previous experimental studies indicate that MRR and depth of cut are sensitive to SoD, Hashish's classic model [176] predicts a relatively flat (weak) sensitivity of depth/MRR to small SoD changes

inside an optimal window, but a strong decay as SoD approaches/exceeds the critical range (often depends on the nozzle diameter).

Multi-pass strategies proposed by Rabani et al. [177] and Hejazi [160] build on this predictability to achieve ply-by-ply removal by compensating for small Δ SoD through adjusted traverse speed/pass. This leads to the conclusion that adopting the AWJM for repair would not only translate to higher control over the extent of machining defects but also allow for greater precision for ply-by-ply milling regardless of the fiber orientation and change of SoD resulting from composite deformation compared to CM techniques. However, the ply-by-ply milling capability of AWJ is primarily suited to step-lap geometries and is more difficult to implement for scarf repairs. AWJ achieves reliable step-lap machining because each step corresponds to a constant-depth cut in which the jet impinges normal to the laminate, resulting in uniform energy dissipation and particle erosion and therefore predictable material removal per pass that enables controlled ply-by-ply milling [59,178]. By contrast, a scarf requires a shallow, continuously varying taper so that the jet-material interaction evolves along the cutting path. Jet kinetic energy decreases with increasing SoD and penetration depth, while the kerf taper produced by jet spreading and energy attenuation cannot be eliminated without dynamically varying nozzle tilt and traverse speed along the surface, which can increase dimensional error and complicate process control [179]. Furthermore, alternating head-on and oblique particle impacts during a

sloped cut can promote non-uniform erosion, fiber pull-out, matrix cracking, and variable surface roughness that cannot be easily compensated through pass overlap or tool-path programming. Consequently, achieving an accurate scarf taper may require a large number of controlled passes or complex five-axis adaptive control to compensate for jet divergence and deflection, which can reduce machining efficiency and repeatability compared with the step-lap configuration [180,181]. Nevertheless, the true advantage of AWJM lies in its potential to greatly reduce repair time by combining the material removal and surface preparation steps into a single operation.

3. Surface preparation

Surface preparation is a critical step in bonded repair applications, directly influencing the strength, fracture toughness, and long-term durability of the bonded substrate [39,118]. The surface preparation process typically involves a series of cleaning and modification steps aimed at achieving the desired surface properties. These steps often begin with cleaning using solvents such as methyl ethyl ketone (MEK) or trichloroethylene to remove contaminants and debris remaining after the damage removal step [182]. Following cleaning, activation of one or two primary adhesion mechanisms is required to achieve high-strength bonding of polymer composites, namely, mechanical interlocking and chemical bonding. Mechanical interlocking occurs when a liquid

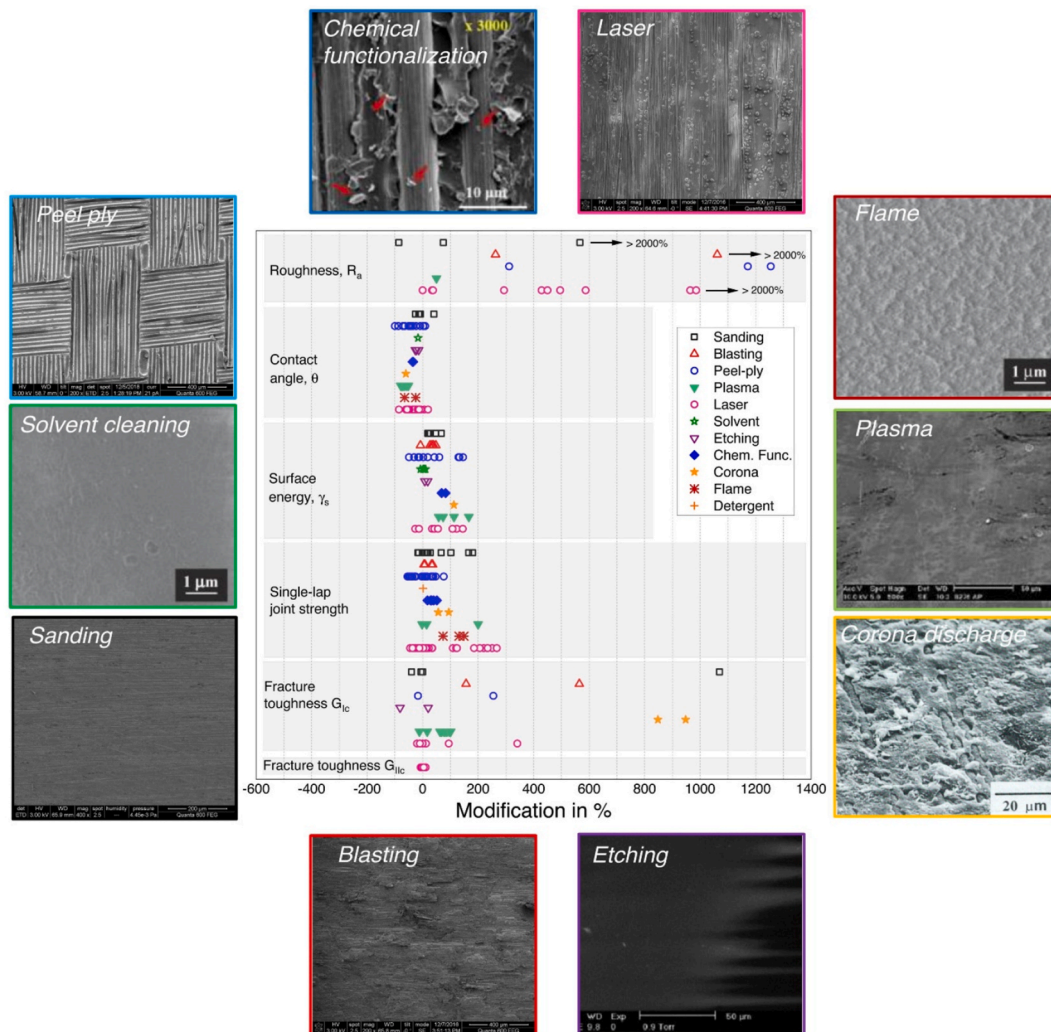


Fig. 9. Surface preparation techniques showing their corresponding surface morphologies and associated effects on surface and mechanical properties (adapted from Ref. [118]).

adhesive penetrates surface pores and cavities and then solidifies, creating a form-fit lock with the substrate. Chemical bonding arises from the formation of molecular bonds, for example, covalent, ionic, or strong polar interactions, between functional groups on the substrate surface and the adhesive [84]. These mechanisms can be activated by different surface-preparation techniques, as illustrated in Fig. 9. Surface preparation methods generally remove a thin layer, typically on the micrometer scale, of low molecular weight material such as the polymer matrix. This typically leads to altering surface roughness, contact angle, surface energy, joint strength, and fracture toughness. Each technique produces distinct surface topographies and chemical or physical characteristics, which directly influence bonding performance and mechanical behavior. Common techniques that provide mechanical interlocking include abrasive blasting, peel ply, sanding, laser treatment, flame treatment, acid-base etching, and plasma treatment. Abrasive blasting, also referred to as sandblasting, propels abrasive particles at high velocity against the surface, thereby removing contaminants and increasing surface roughness [183]. Peel ply is a woven sacrificial fabric that is co-cured on the composite surface and subsequently peeled off prior to bonding, resulting in a clean and textured surface [184]. Sanding employs an abrasive medium, such as sandpaper, to abrade the surface, removing weak boundary layers and imparting microscale roughness [185]. Laser treatment is a non-contact method that uses pulsed laser irradiation to remove surface resin and contaminants while simultaneously modifying surface morphology. It can also generate chemical species that increase surface energy [186]. Plasma treatment exposes the surface to an ionized gas, which simultaneously cleans the surface and substitutes surface atoms with reactive species, increasing surface energy and creating new bonding sites [187]. It is important to note that these topography-driven treatments commonly also induce chemical activation because material removal exposes fresh polymer and fiber, and the resulting surface damage and energetic conditions generate oxidized species and free radicals that increase the polar component of surface energy and create reactive groups that promote adsorption and covalent bonding [118]. On the other hand, methods that primarily activate the surface by chemical means are chemical functionalization, which replaces surface atoms with specific functional groups to provide reactive sites for covalent bonding [188], corona discharge, which applies high-voltage ionization to generate ozone and free radicals that oxidize the surface, thereby significantly increasing surface energy and wettability for adhesion [189], and acid-base etching is a wet chemical process in which the surface is immersed in acidic or alkaline solutions to chemically dissolve and roughen the surface, thereby exposing fresh material [190]. Among the techniques presented in Fig. 9, only blasting and sanding are currently employed in the aeronautical industry for structural repair of composites. Both methods are suitable for controlled depot environments. All other techniques shown in Fig. 9 remain largely limited to academic investigations.

Following these treatments, the surface is generally rinsed with distilled water and isopropyl alcohol (IPA) to remove residual particles and thoroughly dried to expel moisture [20,191,192]. Inadequate surface treatment can lead to poor interfacial adhesion and premature joint failure [193,194], whereas well-executed preparation enhances bonding through improved chemical compatibility and mechanical interlocking between the adhesive and the composite substrate [191,195]. Therefore, the surface preparation step is considered one of the most important and time-intensive stages of the repair process [115]. The complexity is compounded by the high level of operator skill required and the reliance on specialized tools and techniques that are distinct from those used for material removal [196]. This often necessitates operators to switch equipment or relocate components to different workstations, which extends repair duration and increases the risk of process variability and the introduction of defects due to the manual nature of many operations. An optimized repair process could be envisioned in which damage removal and surface preparation are conducted simultaneously, without introducing defects to the material. This concept arises from the

similarity between the two processes, as both involve material removal but at different scales. While damage removal typically targets the elimination of substantial volumes of compromised material, surface preparation focuses on the removal of a very thin layer of the matrix to prepare the substrate for effective bonding. In this sense, surface preparation may be regarded as a controlled-depth milling process requiring extreme precision. CM techniques, whether manual or automated, are not well-suited for such applications, as they lack the required depth control and resolution. This limitation arises from several factors, including tool wear, tool deflection and vibration, part distortion due to residual stress, and variability in ply thickness. In addition, due to the abrasive nature of carbon fibers, the effective depth of cut varies with the geometry of the cutting tool as a result of rapid wear. These effects increase the risk of over-machining or under-preparing the bonding surface, which can compromise repair quality [197]. In contrast, when the AWJ process is used, the depth of cut is not influenced by structural distortion or variations in ply thickness. This behavior can be attributed to the jet acting as a flexible tool that maintains a relatively consistent material removal rate, which is primarily governed by the kinetic energy of the jet [159]. Other non-conventional machining techniques, such as laser machining (LM) and electrical discharge machining (EDM), can also achieve the level of depth control required for surface activation. However, these techniques are not commonly used for surface preparation before bonding, as they can induce undesirable thermal effects, including heat-affected zones, localized burning, and matrix degradation [198,199].

3.1. Surface preparation using abrasive water jet machining process

AWJM was proven to be a more suitable alternative to CM in the context of removing the damaged zone of composite bonded repairs. The process eliminates the thermal damage associated with heat-sensitive polymeric matrices, thereby preserving surface characteristics and adhesion properties. The variety of AWJM parameters provides greater control over material removal rate. Potential concerns regarding abrasive embedment within the bond-line arise because retained particles can disrupt the surface topography, decrease the adhesive contact area, and create stress concentrations that impair fracture toughness and long-term performance [84]. However, research indicates that selecting optimized AWJ parameters can reduce contamination to negligible levels of less than 1% of the treated surface. In fact, these embedment rates are considered comparable to the contamination levels found in standard industrial sandblasting [154,186]. Due to these advantages, researchers have been motivated to investigate the suitability of AWJM for surface preparation in the context of bonded repairs. In this regard, researchers vary AWJM parameters to remove a thin layer of the composite matrix, thereby generating a spectrum of surface textures. Depending on the chosen settings, distinct surface topographies can be produced, each associated with different bonding performance outcomes. Typically, three representative surface conditions are defined, namely *good/soft*, *medium*, and *poor/harsh*. The quality of the machined surface is assessed by material-removal depth, crater volume, residual matrix content, and overall topographical uniformity. “good” surfaces generally exhibit low magnitudes across all these metrics, whereas “poor” surfaces present the highest. Although these three conditions can be produced on virtually any composite system, the specific combination of machining parameters may differ among materials. Fig. 10 illustrates the AWJM texturing process and provides representative examples of these conditions for both CFR/epoxy and CFR/Onyx substrates.

Sourd et al. [145] compared the use of AWJM and sandblasting for surface modification of 3D woven CFRP composites before adhesive bonding. By varying WP, TS, and SoD, a range of topographic conditions on composite specimens was obtained with machining depths less than 100 μm , a range proven critical for preventing degradation of tensile strength and fatigue endurance [200,201]. The textured surfaces were

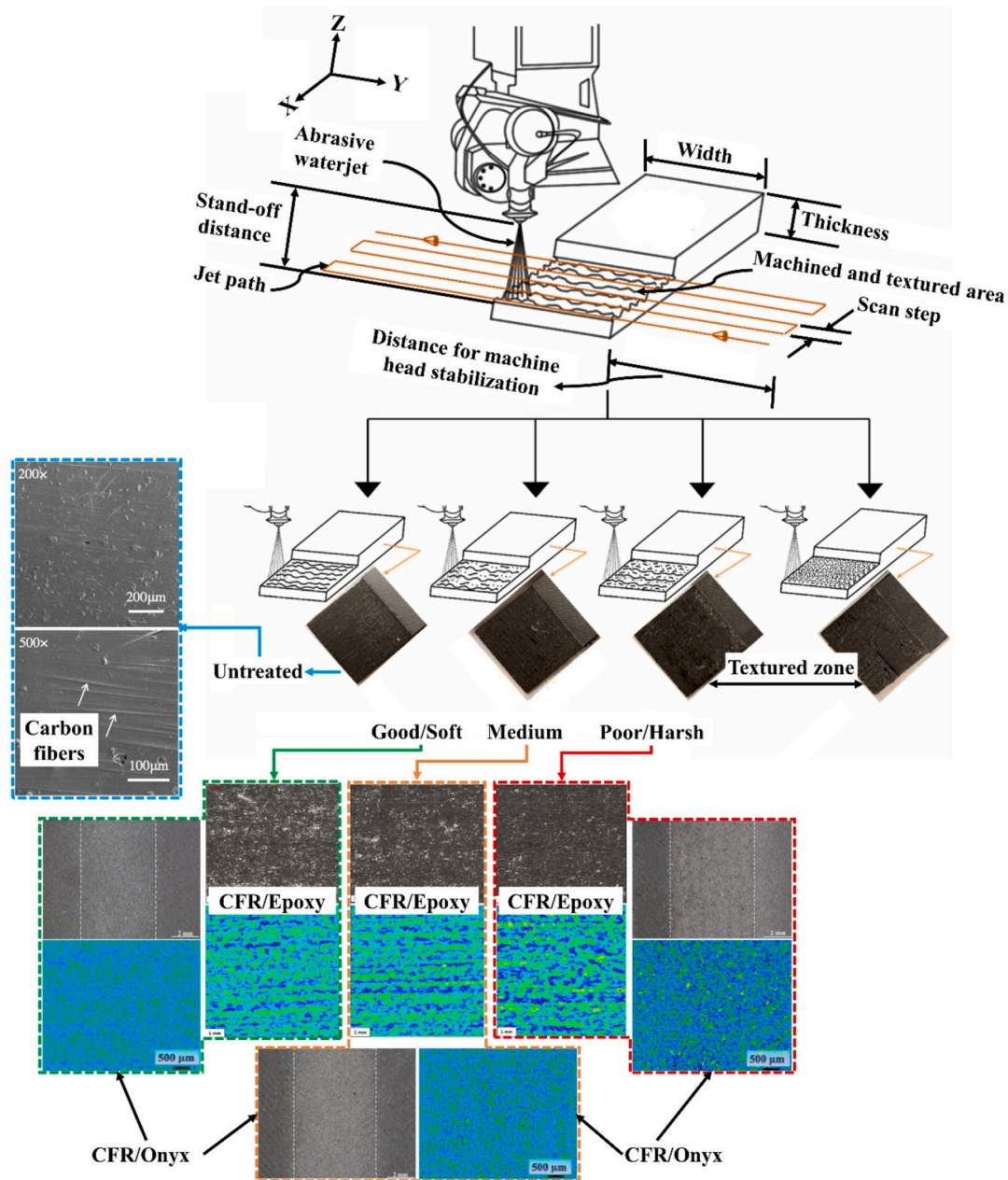


Fig. 10. AWJM texturing setup and representative “good,” “medium,” and “poor” surface-quality conditions for different composite material systems. Image sources: CFR/epoxy micrographs - [204], AWJ texturing process schematic - [205], CFR/Onyx micrographs - [203], SEM images of untreated CFR/epoxy - [206]).

subsequently bonded using an epoxy adhesive film, and their interfacial performance was evaluated through Double Cantilever Beam (DCB) testing. Compared to the sandblasting process, fracture toughness (strain energy release rate in mode I, G_{Ic}) was enhanced by up to 49%, with the potential for increases as high as 60%, depending on texturing optimization (Fig. 11a and b). This increase in G_{Ic} was explained by the fact that the “poor/harsh” conditions, which produced macro-craters, reduced adhesive porosity by 20% compared with the “good” condition, which produced micro-craters. This reduction is attributed to the larger crater geometry, which allowed trapped air in the adhesive layer to escape more easily during curing under the same applied heat and pressure. To the best of our knowledge, no published studies have established a quantitative correlation between AWJM-textured surface metrics and mixed-mode or mode II fracture energy. Fréguelin et al. [202] showed similar results for thermoplastic polyether ether ketone (PEEK)-based CFRP. They evaluated the influence of AWJM parameters,

including abrasive size, pressure, and traverse velocity, on surface morphology and bonding performance. Comparative analysis with alternative surface preparation methods, such as Pure Water Jet (PWJ) cleaning and isopropyl alcohol (IPA) degreasing, was also performed. Single lap shear (SLS) testing demonstrated that AWJM texturing achieved the highest bond strength, surpassing that of untreated samples and those prepared with PWJ cleaning or IPA degreasing. It is important to note that these studies consider arithmetic average roughness (R_a) as an inadequate metric for evaluating bonding performance because it is a 2D metric that overlooks important morphological features. Instead, S_a and C_v both improve surface characterization by describing three-dimensional topography rather than planar roughness. S_a provides the areal distribution of surface heights, whereas C_v measures the actual volume of depressions (craters, voids, and valleys). Because volumetric damage more directly produces stress concentrators, C_v frequently shows higher correlation coefficients with mechanical properties such as

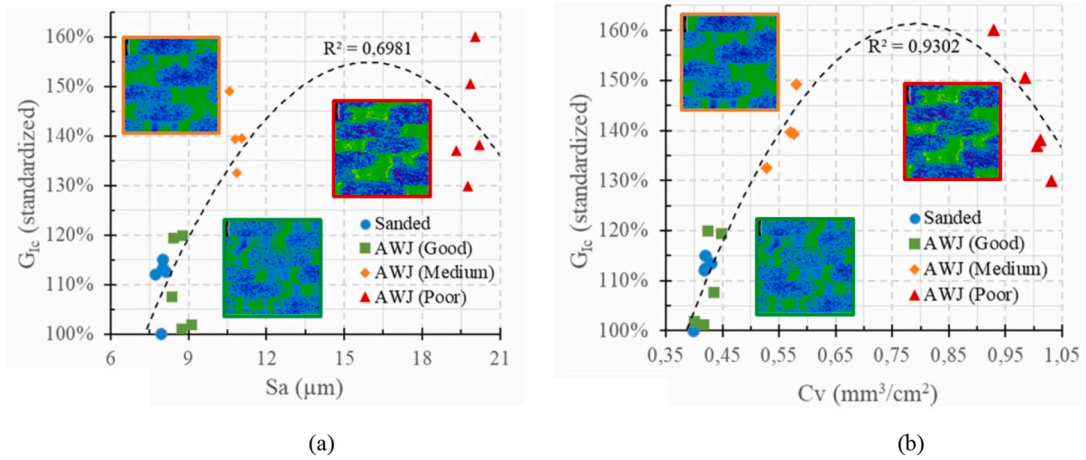


Fig. 11. Influence of AWJM texturing on mode I fracture toughness of woven carbon/epoxy bonded joints as a function of (a) arithmetic mean height, (b) crater volume (adapted from Ref. [145]).

fracture toughness, ultimate tensile strength, and fatigue limit than S_a [160,203]. Because these 3D metrics capture both the areal distribution and volumetric manifestation of impact-induced features, they provide the foundation upon which predictive models can achieve high accuracy.

Frequelin et al. [207] demonstrated that the surface morphology of AWJM-textured thermoplastics can be predicted with a remarkable 94% accuracy using a semi-analytical model that simulates the stochastic nature of abrasive particle impacts. By representing these impacts as arrays of regular tetrahedral craters, the model translates random

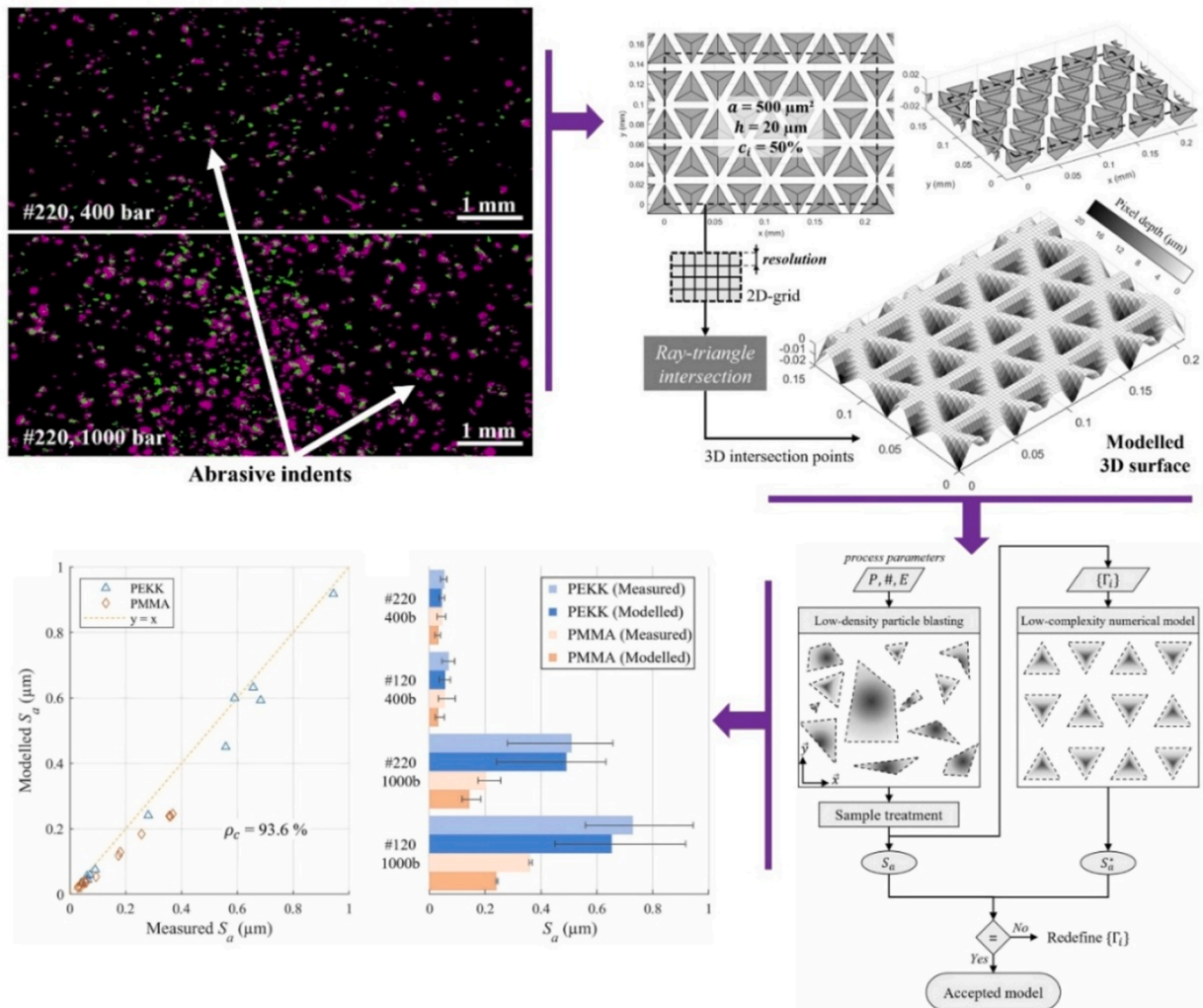


Fig. 12. Predictive modeling of AWJM-generated surface morphology (adapted from Ref. [207]).

AWJM interactions into geometrically consistent forms, enabling computation of key 3D parameters such as S_a and C_v (Fig. 12). In doing so, it reframes AWJM texturing from a process-parameter-driven technique to a morphology-oriented approach, where surface features critical to adhesion and load transfer can be purposefully engineered. This allows for the targeted control of adhesion-critical surface features that ensure the substrate takes up the maximum amount of mechanical stress, representing a significant leap toward accurate predictions of bond-line performance. Nonetheless, realizing its industrial potential will require extensive empirical tests linking mechanical indicators to S_a and C_v metrics, together with further refinement to ensure generalizability across diverse polymers, adhesives, and operating conditions.

Building on these advantages, several commercial manufacturers have developed portable AWJM platforms for on-site composite repair (Fig. 13), among which Bayab has been particularly notable. Bayab's portable system enables in-situ, ply-by-ply machining of composite components up to 3–9 times faster than conventional manual grinding and has been reported to yield about 40% higher shear strength than sanding, thereby permitting structural restoration without component dismantling and streamlining repair operations. Following the development of such platforms, Airbus qualified these portable AWJM systems for in-situ repair of the A350-900 fuselage [208,209]. Although such OEM qualifications demonstrate the technical feasibility of AWJM for specific repair cases, care should be taken not to equate manufacturer-specific qualifications with regulatory acceptance. Regulatory authorities, including the Federal Aviation Administration (FAA) and the European Union Aviation Safety Agency (EASA), require documented evidence that the final manufactured product meets structural and safety requirements, typically through rigorous validation and independent review. Therefore, the certification of the portable AWJM for the A350-900 fuselage remains context- and data-specific and does not constitute normative, fleet-wide standardization, nor does it imply acceptance for use by other aircraft manufacturers. In fact, existing regulatory and industry documents governing bonded composite repairs, including ASME PCC-2 [210] and ISO 24817 [211] for adhesively bonded sleeves and wraps in the oil and gas sector; FAA AC 43-214A [212] and EASA AMC 20-29 [23] for aircraft bonded repairs, and OEM, class, or industry guidance for wind turbine blades [213,214], provide comprehensive frameworks for repair design, material qualification, adhesive selection, curing, and inspection criteria. However,

these standards presuppose conventional manual or mechanical surface preparation techniques and defer cutting and material-removal methods to approved repair data or engineering judgment. To date, no consensus or regulatory standards explicitly recognize AWJM as a validated process for bonded composite repairs. Consequently, several critical aspects remain unstandardized, including validated AWJM process windows, quantitative surface-morphology metrics linked to adhesive performance, residue contamination thresholds, cleaning procedures, the influence of AWJM on adhesive curing, long-term durability, and mechanical behavior across a wide range of materials and texturing configurations. Addressing all the above deficiencies necessitates dedicated experimental programs to establish process-structure-property correlations and to develop rigorous qualification methodologies. Ultimately, the integration of such results into sector-specific normative frameworks will be essential before AWJM can be routinely adopted for certified bonded repair applications. Overall, AWJM offers a promising opportunity to combine machining and surface preparation in a single step, potentially reducing repair time while enhancing adhesive bonding performance, and represents a significant advancement in contemporary bonded composite repair methodologies.

4. Structural health monitoring (SHM) of repaired composites

The multitude of defects that can develop during composite repairs, as shown in the previous sections, even under controlled conditions, poses significant challenges for accurately assessing their impact on structural integrity and long-term performance. The difficulty in producing consistent samples with identical defect characteristics for experimental evaluation further complicates the accurate assessment of repair strength and durability. In this regard, SHM has emerged as a promising approach to overcome the limitations of traditional NDT methods. Unlike NDT, SHM provides continuous, real-time monitoring of a structure's condition throughout its operational life. It involves integrating sensors within the bond-line or within patch/parent components, enabling real-time tracking of damage initiation, propagation, and location [215,216]. Despite the complex procedures and the variety of defects generated during repair, SHM can facilitate the widespread adoption of bonded repair technology by allowing for condition-based maintenance, reducing unnecessary inspections, faster validation and certification of repair methods, supporting data-driven process



Fig. 13. In-situ composite repair of aircraft components using a portable AWJM system [209].

improvements, longer in-service life and lower lifecycle cost. In the context of composite bonded repairs, SHM research has primarily focused on three key technologies: fiber optic sensors, piezoelectric sensors, and piezoresistive sensors, which will be discussed in detail in subsequent sections. A graphical representation of these Structural Health Monitoring technologies as applied to bonded repairs is presented in Fig. 14.

4.1. Fiber optic sensors

Fiber Optic Sensors (FOS) are advanced sensing technologies derived from optical fiber systems. Their operation is based on the modulation of light properties such as intensity, phase, wavelength, or polarization, by external physical parameters like strain, temperature, or pressure. These modulations are subsequently analyzed to extract quantitative information about the measured parameters [217,218]. FOS are

characterized by their immunity to electromagnetic interference, light-weight construction, long operational lifespan (up to 20 years), low power consumption, and minimal signal attenuation over large distances, all of which have contributed to their widespread use in SHM applications [122,123,219]. A typical optical fiber consists of three main components: (i) the core, responsible for transmitting light signals and is usually made of silica; (ii) the surrounding cladding, also silica but with a lower refractive index, enabling total internal reflection to confine light within the core; and (iii) an outer coating, which provides environmental protection and guards against external damage [220,221]. FOS are broadly categorized based on their working principle (e.g., intensity, phase, or wavelength modulation), spatial positioning (e.g., point, distributed, or quasi-distributed sensors), and measured parameters (e.g., physical, chemical, or biological) [222]. Among the various FOS types, Distributed Fiber Optic Sensors (DFOS) and Fiber Bragg Gratings (FBGs) are the most widely used for monitoring the health of

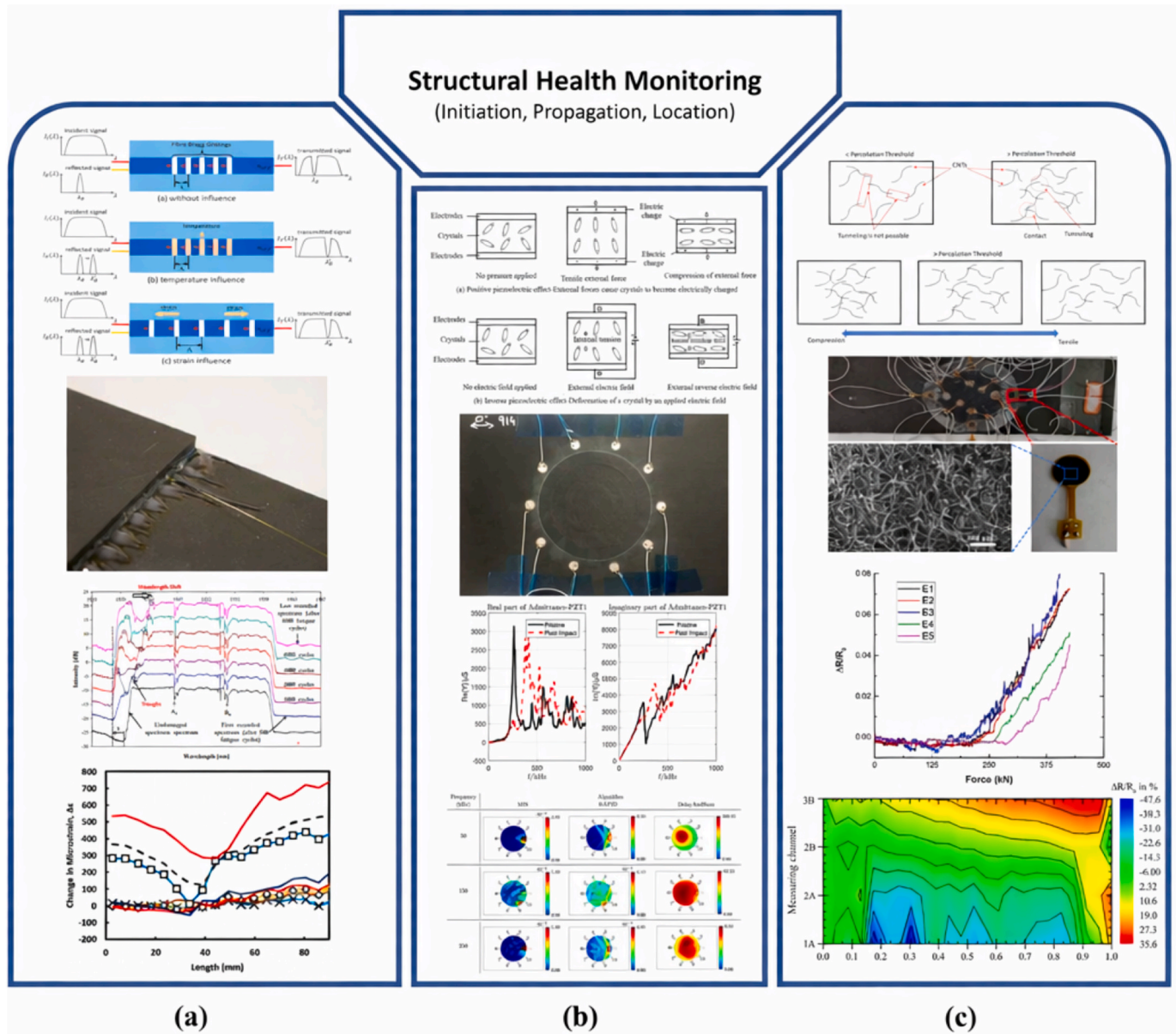


Fig. 14. Graphical abstract of structural health monitoring sensor types in bonded composite repairs: (a) Fiber Optic Sensors (FOS) for monitoring strain redistribution and crack propagation - [223–226] (top → bottom), (b) Piezoelectric Transducers (PZT) for high-sensitivity localization of delamination and bond-line disbands - [227] (top) [228], (second-fourth), (c) Piezoresistive Sensors (PZR), such as carbon nanotube networks, for the detection of early damage initiation and propagation, like microcracking and debonding through resistance increases that disrupt conductive pathways - [229] (second) [230], (third) [231], (fourth).

composite structures.

DFOS relies on light scattering mechanisms to detect variations in strain, temperature, or other parameters along the fiber length. They utilize the entire optical fiber as a continuous sensing medium, enabling spatially resolved, continuous measurements without requiring discrete sensing elements or multiple wavelength channels [232,233]. This approach results in less added weight to the original structure and lower wiring complexities, offering a cost-effective and efficient solution for monitoring large-scale structures, such as bridges, pipelines, and aircraft components [234,235]. On the other hand, FBGs are point sensors that operate based on periodic modulations of the refractive index inscribed into the core of an optical fiber [236]. These periodic variations create a grating structure that reflects a specific wavelength of light, known as the Bragg wavelength (λ_B) and is given by equation (1):

$$\lambda_B = 2n_{\text{eff}}\Lambda \quad (1)$$

where n_{eff} is the effective refractive index of the core and Λ is the grating period [223,237]. When external physical quantities such as strain or temperature are applied, they induce changes in the fiber's local refractive index and grating period, leading to shifts in the Bragg wavelength. These shifts correlate with the applied quantity, with typical sensitivities of approximately 1 p.m./ $\mu\epsilon$ for strain and 10 p.m./ $^\circ\text{C}$ for temperature [238,239]. The direction of the wavelength shift depends on the nature of the applied load: tensile strain and increasing temperature typically cause a shift to longer wavelengths, while compressive strain and decreasing temperature lead to a shift to shorter wavelengths [240]. One of the key advantages of FBG technology is its multiplexing capability, which allows for the integration of multiple sensors along a single optical fiber. This is achieved by encoding sensing information in distinguishable features of light, such as wavelength, time, or frequency, allowing each sensor to operate independently. This multiplexing ability positions FBGs as a type of quasi-distributed sensor, where multiple point sensors are integrated into a single fiber, but each sensor provides localized measurements [241]. By altering the refractive index modulation along the fiber, different types of FBGs can be created, such as Chirped Fiber Bragg Gratings (CFBG), Tilted Fiber Bragg Gratings (TFBG), and Phase-Shifted Fiber Bragg Gratings (PSFBG), among others [242]. Each variation addresses specific sensing and signal-processing needs. For example, CFBGs have a varying grating period along the fiber, resulting in a broad reflection spectrum, with shorter wavelengths reflected in areas of smaller grating spacing and longer wavelengths reflected in areas of larger spacing. This characteristic enables CFBG to map spatial variations of strain or temperature along their length, making them particularly suited for detecting gradients or discontinuities in physical parameters [243].

Despite these advantages offered by DFOS and FBG, the main challenges associated with FOS concern directional sensitivity, cross-sensitivity between strain and temperature (necessitating compensation tools such as positioning two FBGs at an angle relative to each other), the complexity and cost of interrogation systems, and fragility under mechanical stress [244–246]. Over the years, extensive research has examined the use of FOS in SHM of composite materials. However, their application in composite bonded repairs has been less thoroughly investigated, with only a limited number of studies currently available on the topic, as summarized in Table 3. The initial implementation of FOS technology relied on static and quasi-static strain-ratio monitoring to assess the integrity of bonded repairs, such as boron/epoxy composite patches applied to cracked aluminum skins. The core mechanism leveraged FBGs to track the strain ratio between an active grating placed in the high-stress, tapered region of the repair and a reference grating located in a region with minimal thermal residual strain. Damage (disbonding or crack growth) was detected by a change in this ratio, reflecting the loss of load-transfer capacity by the adhesive bond. However, in some implementations, particularly surface-mounted sensors, severe strain gradients induced by localized damage propagation

caused the FBG's reflected spectrum to distort (exhibiting multiple peaks or broadening). In those cases, measurements were often taken at zero load to accurately quantify residual strain changes, thereby preventing continuous in-service monitoring. Subsequent research advanced to spectral diagnostic mechanisms designed to either utilize or simplify the interpretation of these complex strain fields. One solution proposed utilizing a long (25 mm) FBG near a crack tip, which addressed the ambiguity of non-uniform strain by converting spectral distortion into a dual-measurement diagnostic tool. The intense local stress field caused the single reflection peak to split into two distinct peaks, a phenomenon attributed to the generation of a secondary local sub-grating. This allowed the sensor to simultaneously quantify the coupon's average stress (via the primary peak) and the highly localized, intense stress near the crack tip (via the secondary peak). Another approach aimed at simplifying the spectrum by employing Chirped FBG (CFBG) sensors embedded in the bond-line of GFRP patch repairs. CFBGs successfully detected disbond initiation under fatigue by manifesting characteristic wavelength shifts and dips, notably avoiding the complex peak splitting seen with standard FBGs under multiaxial residual strains. Nevertheless, ambiguity persisted, as experimental findings determined that monitoring was only consistently clear at the low-wavelength (lw) end of the sensor; consequently, practical deployment necessitated the use of two parallel CFBG sensors with opposite polarities to ensure reliable detection coverage across both vulnerable repair edges. While these studies were able to convert complex static strain gradients into measurable parameters, these FBG-based techniques were predominantly developed and characterized under static or quasi-static load conditions, severely limiting their applicability for capturing the complex strain fields associated with damage progression during real-world, high-frequency dynamic operations. This subsequently drove the development of high-speed, full-spectral interrogation techniques. Experiments involving FBGs embedded in CFRP single lap joints utilized a specialized interrogator capable of acquiring the full spectral response at a high rate (100 kHz) during continuous multicomponent harmonic excitation frequency range that was representative of that typically experienced in flight. Damage was identified through spectral frequency analysis (Fast Fourier Transform and Short-Time Fourier Transform) when the joint's strain response transitioned from linear behavior toward strong non-linearities and chaotic vibration, caused by the complex, non-uniform strain field induced by irregular defect growth in the adhesive layer. This shift in dynamic signature provided a highly sensitive, real-time indicator of progressive fatigue damage. Another advanced study utilized FBG sensors for continuous real-time monitoring of the bond-line integrity by directly correlating with the FBG's thermally induced Strain Sensitivity (ST). This approach relies on the principle that bond degradation alters the mechanical strain transfer from the structure to the fiber, which is measured as a change in the FBG's sensitivity to temperature-induced strain during the active local induction of thermal changes. Experiments demonstrated that low bonding quality or simulated disbond defects caused the FBG's temperature-dependent apparent strain sensitivity to increase significantly, reaching up to ~50% near low-quality bonding areas, indicating damage. Despite the enhanced sensitivity and temporal resolution provided by specialized FBG techniques, the fundamental limitation of discrete spatial coverage remained, driving the adoption of continuous distributed fiber-optic sensing (DFOS) using techniques such as Optical Backscatter Reflectometry (OBR) and Swept-Wavelength Interferometry (SWI). This mechanism excels in achieving continuous, high-spatial-resolution strain data over the entire joint length via a single fiber. OBR technology was successfully validated for monitoring Fatigue Crack Growth (FCG) in woven CFRP single lap joints by precisely tracking the displacement of the minimum negative strain peak in the continuous Back Face Strain (BFS) profile, confirming its utility as an evolution of earlier FBG-array-based BFS techniques. Furthermore, SWI-based DFOS was instrumental in analyzing the damage propagation in a step-lap CF/epoxy joint under tensile fatigue loading. The sensor was bonded

Table 3
Summary of FOS applications in SHM of metallic/composite bonded joints.

Limitations	Severe strain gradients degraded signal reflection/voltage measurements, suggesting challenges for accurate strain readings.	Limited spatial coverage of a single sensor necessitates minimizing vulnerable wiring and associated connections and using large arrays.	Monitoring was only reliably correlated on the side experiencing a strain increase, suggesting the need for dual-sided arrays.	Peak-splitting in the FBG spectral response due to non-uniform strain fields complicated accurate dynamic measurements.	Out-of-plane deformation of the SL joint prevented direct validation using 2D DIC on the backface.	Results were preliminary and based on one single test (one specimen lasted for 59,913 fatigue cycles).	The localized change in adherend thickness (stepped geometry) caused greater localized strain measurement at the thinner section, complicating interpretation.	Changes in the spectra at the high-wavelength (hw) end were more difficult to detect; recommended to use two parallel CFBG sensors.	The single 2 mm FBG near the patch edge showed a larger gradient (0.043 nm/kN) due to exposure to higher and less uniform stresses.	Results are preliminary and require further testing on samples with accurately controlled manufacturing conditions.	Measurement precision slightly declined for larger disbonds
Damage identification	Damage was identified by the loss of sensor signal due to severe strain gradient, followed by restoration of the reading when the patch delaminated	Damage was indicated by an increase in transmitted signal intensity (light transmission).	The position of the maximum positive strain variation was used to locate the crack tip.	Transition toward quasi-periodic motion and chaotic vibration indicated accumulated damage.	The minimum peak position identified the crack front.	The minimum peak position identified the crack front.	A gradual change in strain followed by a significant, rapid increase in the last 3500-4000 cycles indicated failure progression.	Distinct spectral dips and continuous shifts at the low-wavelength (lw) end of the spectrum were tracked over fatigue cycles.	Spectral splitting of the long FBG was used for monitoring regions with localized stress measurement.	High <i>ST</i> identified low-quality bonding or defects.	Gradual strain evolution in hybrid joints and rapid escalation in bonded joints confirmed damage.
Output Signal	Residual Strain vs. Loading Cycles/ Change in the ratio of the input and output signal voltage.	Transmitted optical intensity (optical power) vs. cyclic loading.	Strain Difference vs. Sensor Position.	Amplitude/ Intensity vs. Frequency	Normalized Strain Profile vs. Position/Length	Position of the Minimum Strain Peak ($L-x_{min}$) vs. Number of Cycles.	Distributed Strain vs. fatigue cycles.	Reflected Spectra (Intensity [dB] vs. Wavelength [nm]).	Peak Wavelength vs. Applied Force and Spectral full width at half maximum FWHM vs. Applied Force.	Thermal Sensitivity (pm/°C) derived from Wavelength vs. Time/Temperature data.	Normalized Distributed Strain vs. Position vs. Fatigue Cycles.
Detection Principle	Monitoring the change in the strain transfer mechanism (strain gradients) over the crack tip and the release of thermal residual strain in the patch due to disbond.	Monitoring spectral mismatch/strain-ratio changes between active and reference gratings caused by the release of thermal residual strain when disbonding begins.	Monitoring highly localized strain field variations (stress concentrations) caused by crack tip proximity, where the maximum variation of longitudinal strain tracks crack progression.	Analysis of the sensor's dynamic response to harmonic excitation to detect transitions from linear elastic behavior to non-linear structural dynamics as fatigue damage progresses.	Monitoring crack propagation by correlating the crack tip position with the minimum (negative) peak in the Back Face (BF) strain profile.	Monitoring fatigue crack growth by tracking the linear relationship between crack length and the position of the minimum peak of the BF strain profile.	Monitoring of distributed strain measurement to detect and track localized damage accumulation and resulting load path changes during fatigue loading.	Monitoring changes in the spatial strain distribution along the chirped grating caused by the growth of disbonds.	Measurement of the stress distribution and strain homogeneity across the repaired crack region, quantified by the linear FBG response and spectral characteristics (gradient, FWHM expansion).	Relying on the principle that bond degradation changes the strain transfer mechanism from the structure to the fiber, thus altering the FBG's Thermal Induced Strain Sensitivity (<i>ST</i>).	Tracking load-sharing transition and the evolution of strain distribution anomalies in the bond-line caused by disbond initiation and progression.
FOS Characteristics	Surface-mounted FBG array: one on the aluminum skin;	Surface-mounted dual FBG (active/reference): active FBG bonded in the	10 FBG arrays were surface-mounted on the side of the joint	One single FBG sensor embedded within the adhesive layer	Single DFOS (OBR) bonded to the surface	Single DFOS (OBR) bent to obtain four measuring	Two DOFS (SWI) are bonded to the outer joint surface	One Chirped FBG sensor embedded in the adhesive bond-line	Specialized Embedded FBG Array: Short (2 mm), long (25 mm), and	Four FBG Sensors embedded in the bond-line	Single DOFS (OBR) bonded to the external surface along the

(continued on next page)

Table 3 (continued)

	three on the patch top surface	tapered high-stress region; reference FBG in a low-strain (strain-free) region.	(backface) of the segments bonded on the back face and two segments on the front face	along the 90 mm overlap region.	multiple arrays (five 1.2 mm FBGs). Sensors were embedded in the composite patch between ply 3 and 4, positioned over the crack.	90 mm gauge region.					
Joint Type	Doubler Repair	Doubler Repair	Single Lap Joint	Single Lap Joint	Step Lap Joint (5 steps)	Doubler Repair	Single Lap Joint				
Material System	Cracked Aluminum skin repaired with a Boron/epoxy patch.	Cracked metallic structure repaired with Boron/epoxy composite patch.	UD CFRP adherends	UD CFRP adherends	Woven CFRP adherends	GFRP adherend repaired with a GFRP patch.	Aluminum coupon with a crack repaired with a Boron/epoxy patch.				
Year/Authors	Jones & Galea (2002) [261]	Baker et al. (2009) [111]	Bernasconi et al. (2011) [262]	Webb et al. (2013) [263]	Bernasconi et al. (May 2015) [264]	Bernasconi et al. (Dec 2015) [265]	Wong et al. (2016) [225]	Rito et al. (2017) [226]	Ikiades (2020) [266]	Di Palma et al. (2023) [267]	Ekladious et al. (2025) [268]

to the external surface of the joint and aligned with the carbon fiber direction. Damage initiation and propagation were identified through the monitoring of micro-strain variations along the fiber length and as a function of the number of fatigue cycles. However, DFOS systems typically trade temporal resolution for spatial coverage: interrogator sampling rates are generally much lower than high-speed dynamic FBG systems and often fall in the tens to hundreds of Hz range, depending on the hardware. A few examples of damage detection methods for different bonded repair configurations are presented in [Fig. 15](#), which illustrates representative FOS placement and damage identification strategies that enable real-time tracking of strain redistribution and fatigue-driven damage.

Additionally, recent research indirectly highlights the potential of FOS technology for monitoring parameters critical to repair applications, such as adhesive cure levels [247–249], humidity [250], and its ability to be embedded within adhesive layers [251] or between composite layers [252]. In applications where FOS are embedded, their sensitivity to moisture and chemicals necessitates the use of protective polymeric coatings. These coatings increase the outer diameter of the fibers to approximately 125–130 μm [253], significantly larger than the diameter of reinforcing fibers in composite materials, which typically range from 6 to 10 μm . As a result, embedding FOS can lead to defects such as resin-rich areas and stress concentrations. Nevertheless, research has shown that these defects can be minimized by selecting FOS with small diameters [221,254,255]. It is important to note, however, that even with reduced diameters, the use of protective coatings can impair stress transfer between the matrix and the fiber, leading to inaccurate strain measurements and necessitating extensive calibration techniques [256]. Another critical issue when embedding FOS within composite layers is their orientation relative to the reinforcing fibers. Minimizing the misalignment between the FOS longitudinal axis and the local ply fiber direction substantially reduces local fiber waviness, resin-rich zones and transverse stress concentrations, and can therefore diminish adverse effects on static strength and fatigue [257]. However, this alignment requirement constrains sensor placement in multi-angle laminates. For example, in case the ply angle does not coincide with the primary loading direction, embedding the FOS parallel to the local fibers may not yield an optimal measurement of the applied load, because most common FOS are predominantly sensitive to strain along their longitudinal axis [258]. As an alternative, FOS can be bonded to the external surface of the patch or parent structure. This approach is less complex, more adaptable, and facilitates easier maintenance. Nevertheless, externally bonded FOS remain vulnerable to damage due to their fragility and require protective measures along their entire length to guard against environmental exposure [257]. Additionally, their location on the surface may limit their sensitivity to damage mechanisms that initiate or propagate within the composite's internal plies or deep within the bond-line of the repair. Collectively, this literature review underscores the effectiveness of FOS for damage detection and monitoring in composite repair applications. Damage localization may be achievable using distributed fiber optic sensors (DFOS) or networks of fiber Bragg gratings [259,260]. However, to date, no research has addressed the application of FOS technology for damage localization purposes on closed repairs on large composite panel repairs, nor assessed their performance under multiaxial loading conditions or when damage orientation does not align with the principal load direction. Consequently, further investigation is required to evaluate and validate FOS's applicability in such practical scenarios.

4.1.1. Piezoelectric sensors (PZT)

The piezoelectric effect is a phenomenon where certain materials generate an electrical charge when subjected to mechanical stress, or deform mechanically when exposed to an electric field [269]. Lead Zirconate Titanate (PZT) sensors take advantage of this effect to function as both actuators and sensors, offering unique capabilities for SHM and composite bonded repair applications [270]. When bonded to a

structure, PZT devices can operate in either passive or active sensing modes. In passive sensing, the PZT acts as a sensor that operates without the need for a power source and detects mechanical waves propagating through the structure due to external events, such as impacts or acoustic emissions generated by the structure's response to loading or damage. Active sensing, on the other hand, requires an external power source for continuous and real-time operation of the PZT as both an actuator and a sensor to detect damage through two primary techniques: Electromechanical Impedance (EMI) and Ultrasonic Guided Waves (UGW).

The EMI method involves exciting the PZT transducer with a high-frequency input, typically more than 20 kHz, using a low harmonic voltage source, to induce mechanical vibrations in the host structure [271]. According to the EMI theory [272]. These vibrations propagate

into the host structure, creating a coupled electromechanical system in which the mechanical impedance of the structure directly influences the electrical impedance of the PZT. Structural damage, such as cracks, delamination, or material degradation, alters the local mechanical impedance of the structure, which is reflected in changes in the PZT's electrical impedance spectrum. These changes manifest as shifts in the resonance frequency and variations in the impedance slope [273]. By comparing the measured impedance spectrum with a reference spectrum (obtained under undamaged conditions), structural damage can be identified. However, the EMI method is a local sensing technique due to the high attenuation of the induced vibrations and their limited propagation range [274,275]. It is commonly used for evaluating localized damage, such as transducer bonding quality, small cracks, disbonds

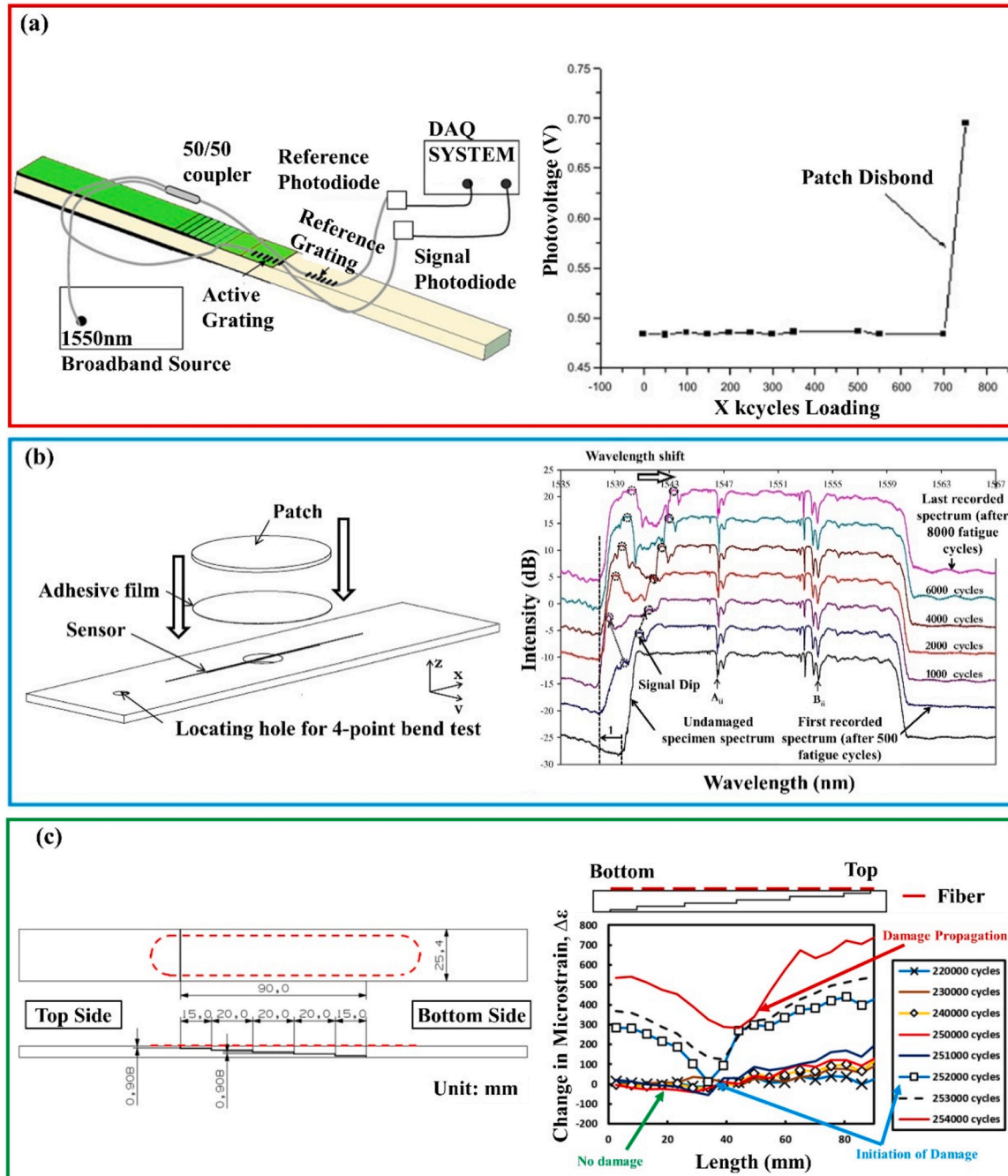


Fig. 15. FOS placement strategies in composite bonded repairs: (a) attached on patch surface [111]; (b) embedded in adhesive bond-line [226]; and (c) attached on bonded stepped-lap coupon surface [225].

between the PZT and the structure, and the degree of bond-line cure [276,277]. Usually, the real part of impedance or admittance can be used for damage detection, while the imaginary part of impedance or admittance can be used for the detection of PZT debonding [278–280]. The technique can be operated in a continuous or periodic mode to enable real-time monitoring.

On the other hand, the UGW technique is preferred for global structural damage detection due to the low energy attenuation and long propagation range of guided waves [281]. These waves propagate across larger areas, making them suitable for damage localization and detection across entire structures. Among UGW techniques, Lamb waves are widely used in SHM applications. Lamb waves are a specific type of guided waves that are typically generated upon exciting the PZT transducer with an alternating frequency, and they can have two main modes, symmetric (S) and anti-symmetric (A) modes. The wave mode depends on the excitation frequency and the structure's thickness [282]. Symmetric waves exhibit in-phase particle motion about the mid-plane of the plate, where displacements on both surfaces occur in the same direction. They are dominant at high frequencies and particularly sensitive to through-thickness defects, such as delamination or voids, as their energy is distributed across the plate thickness [283,284]. On the other hand, antisymmetric waves feature out-of-phase particle motion, with displacements on one surface opposite each other. They are dominant at low frequencies but can also exist as higher-order modes at higher frequencies. The energy of antisymmetric modes is concentrated near the plate surfaces, making them ideal for detecting surface and near-surface damage, such as surface cracks and adhesive disbands [285,286]. As Lamb waves propagate through a structure, they interact with its features and damage, which can lead to measurable changes in wave characteristics such as amplitude, phase shift, and time of flight (ToF) [287]. These modified waves are detected by PZT transducers in one of two primary modes: pitch-catch [288] and pulse-echo [289], as illustrated in Fig. 16. In the context of Structural Health Monitoring (SHM) for composite bonded repairs, PZT transducers are extensively used for damage detection and localization. The transducers can either be surface-bonded to the parent structure outside the repair area or embedded within the composite layers of the patch [290].

Damage detection is based on comparing the wave signal characteristics between pristine and damaged states of a structure [291]. The extent of the damage encountered by any specific wave path, reflected in changes in wave characteristics, provides quantitative measures of the damage severity [292]. These measures are represented as damage indices, which indicate the structural condition along a given transmitter-receiver path. A damage index that exceeds a pre-determined or statistically derived threshold typically signals the presence of damage [293]. Methods widely used to compute damage indices include statistical outlier analysis, principal component analysis (PCA) projections, root-mean-square deviation (RMSD) of waveform or spectrum deviation, mean absolute percentage deviation (MAPD), and cross-correlation deviation (CCD) [294,295]. The principal distinction among these methods lies in their mathematical formulation and, thereby, their respective sensitivity to aspects such as thresholding strategy, multivariate correlation structure, absolute amplitude change, relative change, and waveform/phase similarity. Nevertheless, they all share the underlying principle of quantifying deviation from a defined healthy baseline and reducing that deviation to a scalar (or low-dimensional) damage index, which is then compared against a detection threshold. Damage localization builds on this principle by using PZT arrays to generate multiple and independent wave paths that interact with the structure. Localization algorithms, such as Minimal Intersection Score (MIS), Delay and Sum (DAS), Direct Path Image Utility (DPIU), neural networks, and Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) [296–300], are then used to calculate differences in wave propagation paths and utilize their features to estimate the location of the damage. As an example, the MIS algorithm [228] calculates the time it takes for the first Lamb wave packet to

travel in an undamaged state and compares it with the damaged state. These differences are used to calculate Path Damage Indices (PDI) for each transmitter-receiver pair. The paths of these signals intersect at various points within the structure, which form potential damage zones. By dividing the structure into regions using Voronoi tessellation and assigning a probability of damage to each region based on the minimum PDI, the critical damage location can be identified. Other damage localization techniques rely on similar fundamental principles but may introduce minor variations to suit specific applications or structural configurations.

Pavlopoulou et al. [102] examined the behavior of a woven CF/epoxy panel that was repaired using a scarf patch following damage due to impact. The panel was examined using lamb waves excited by eight surface-bonded PZT transducers under longitudinal tensile loading, operating in pitch-catch mode. Four of the eight PZT transducers functioned as actuators, while the other four served as sensors; all were placed outside the repair area to determine damage initiation. The damage index was calculated from the attenuation of the peak-to-peak amplitude with respect to the loading level, enabling the detection of damage along different paths. The results were in good agreement with the DIC results showing good ability of PZT to monitor initiation of damage and a good correlation between the propagation route and the expected developed internal damage at each area of the panel. In another research by the author on the same test parameters and loading condition [301], they expanded damage detection techniques and used the outlier analysis, linear and non-linear principal component analysis. They showed that the damage paths calculated using all these techniques were in good agreement with the DIC results and physical observations, demonstrating their applicability for damage prognosis. Lambinet et al. [302] evaluated RAPID algorithm for a step-sanded composite patch repair weakened by 4-point bending fatigue and impacted to induce BVID. RAPID quantifies differences between pristine and damaged states using the Signal Difference Coefficient (SDC), which is computed for each transmitter-receiver pair. These SDCs were then combined probabilistically to create a damage probability map. Twelve surface-bonded PZT transducers in pitch-catch mode were used to monitor the repair. The authors showed that damage was successfully detected and approximately localized. However, the precision of localization was affected by the limited number of transducer paths and some sensor failures due to the impact loading. Despite these limitations, the damage was identifiable from the generated probability maps, confirming the effectiveness of RAPID in complex composite structures. In an extended research, Lambinet et al. [228] utilized the symmetric and antisymmetric lamb waves for detecting and localizing delamination in the bond-line caused by low velocity impact (LVI) in a step-lap CFRP panel using damage localization algorithms, namely MIS and compared it with DAS and RAPID algorithms. Ten PZTs are placed circumferentially on the panel and around the circular repair. They employed the EMI method before and after conducting the LVI to check for faulty or detached sensors near the impacted region. They noticed that near the impacted region, one sensor had a significant change in the imaginary part of admittance before and after impact, which indicated damage and it was validated that damage had indeed occurred. Under varied temperature and vibration influence, they showed that MIS, DAS and RAPID can be successfully used for damage localization, but MIS outperformed them in terms of accuracy and robustness to temperature and external vibrations (Fig. 17). The authors also noted that higher frequencies in the range of 200–300 kHz were more robust to vibrations compared to lower frequencies (50 kHz), which indicates the importance of selecting the suitable frequency range for damage detection and localization. Habib et al. [300] utilized DPIU to localize and quantify disbands in bonded composite repairs. DPIU is based on mapping damage indices to a graphical representation, where regions with higher probabilities of damage are highlighted using a color scale. PZT transducers were surface-mounted and arranged in a pitch-catch configuration on carbon fiber substrates bonded with boron patches using FM73 film. DPIU

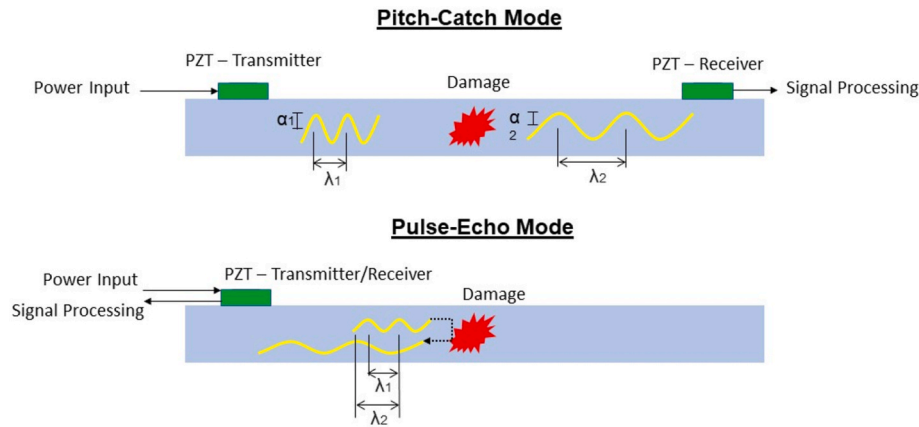


Fig. 16. PZT primary operating modes.

results correlated strongly with C-scan ultrasound validation, accurately identifying damage progression. However, DPIU tended to overestimate damage at high fatigue cycles and struggled with small disbands ($<0.15 \text{ in}^2$). Furthermore, Feng and Aliabadi [303] embedded an array of five PZT sensors inside a CFRP patch which is externally bonded to a CFRP panel for the detection of artificial delamination along the bond-line and artificial damage on the surface of a composite repair patch through the use of UGW. The authors employed the EMI method to assess the bonding properties between the PZT transducer and the repair patch. Based on analyzing the slope change of the imaginary part of the admittance, no slope change was observed, indicating that the bonding between the PZTs and the patch was intact and strong. Furthermore, the authors utilized the damage index correlation coefficient and DAS algorithm for damage detection and localization, respectively. DAS aligns the residual signals collected from different transmitter-receiver pairs by applying time delays calculated based on the expected time of flight of Lamb waves propagating through the structure (Fig. 18).

The delayed signals are then summed to amplify contributions from damaged regions, resulting in a spatial map that highlights damage locations. The contrast at each pixel is calculated based on signal envelopes and time-of-flight data [304]. The results showed that the smart repair patch can locate the artificial delamination using three PZT transducers and surface-mounted artificial damage using four PZT transducers. However, the viability of this technique under mechanical or fatigue loading was not addressed. Based on the literature review findings, PZT sensing has demonstrated significant potential for continuous monitoring of composite bonded repairs, showing promise in detecting and localizing damage with high precision. However, it is important to note that very few studies have investigated damage localization in composite repairs using PZT under simultaneous application of mechanical loading. This is a significant gap in the current literature because in bonded composite-repair, the wave propagation paths are influenced not only by the host laminate but also by the repair patch, the adhesive layer and any interface debonding; as a result, the mapping between the damage index and actual damage size or location may be less direct, and environmental/instrumentation variability (e.g., sensor bonding, adhesive aging) must be explicitly addressed under mechanical loading. In addition, studies on the embedment of PZTs within repair patches or along the bond-line remain very limited, particularly under mechanical loading. This limitation arises from the risk of short-circuiting caused by carbon fibers, the need for additional shielding to prevent electromechanical interference and the extensive wiring required for PZTs [124]. This represents a promising area for future research to establish the feasibility and reliability of this method in bonded repairs. Furthermore, data acquisition and processing for Lamb waves is very difficult due to wave dispersion, which causes the wave speed to vary with frequency. Dispersion complicates damage

identification, especially at high frequencies where waveforms become difficult to interpret [305]. Lowering the frequency reduces dispersion but also lowers sensitivity to minor cracks [306]. Therefore, selecting the optimal frequency range and employing advanced signal processing techniques are essential to balance sensitivity and reliability but contribute to the cost and complexity of the monitoring process, particularly during operating conditions [307]. Moreover, external factors such as environmental vibrations and temperature fluctuations can alter wave characteristics and lead to false positives, thereby requiring compensation algorithms that increase system complexity [308,309]. Another challenge lies in the energy demands of PZT transducers, especially when a sparse PZT network is used [310]. Although these sensors are relatively cheap, reliable damage localization requires as many PZT pairs as possible; as a result, they require significant energy consumption for active sensing, which is crucial for real-time monitoring given that structural damage can occur unexpectedly [304]. Researchers are addressing this limitation through solutions like event-triggered wireless PZT sensing [311], which activates monitoring only under specific conditions. Further research is necessary to refine and implement these technologies in practical repair scenarios.

4.2. Piezoresistive sensors (PZR)

The piezoresistive effect is the change in a material's electrical resistance caused by applied mechanical stress or strain; unlike the piezoelectric effect, it requires an external excitation source and is therefore considered an active sensing mechanism [312]. A material's fundamental electrical properties are governed by its bandgap, which dictates how mechanical strain influences conductivity [313,314]. Purely insulating polymers exhibit negligible piezoresistivity even when high electric fields or thermal excitation, due to a very large bandgap. In such polymers, free carriers are absent and electrons remain strongly localized within covalent bonds that form long molecular chains, further restricting their ability to move freely [315,316]. However, this limitation can be overcome by introducing conductive fillers, which transform polymers into piezoresistive materials. The transition from an insulating to a conductive state occurs when a sufficient concentration of conductive fillers forms a continuous network within the polymer, enabling electron transport. At low concentrations, conductive particles remain isolated within the matrix, preventing the formation of a conductive pathway and inhibiting electron flow. However, as the concentration increases, a critical threshold, known as the percolation threshold, is reached, beyond which a continuous conductive network emerges, allowing electron transport through direct physical contact between conductive fillers under an electrical field [317–319]. Within this percolated network, conduction occurs in a manner analogous to metallic conduction, as electrons can move through interconnected

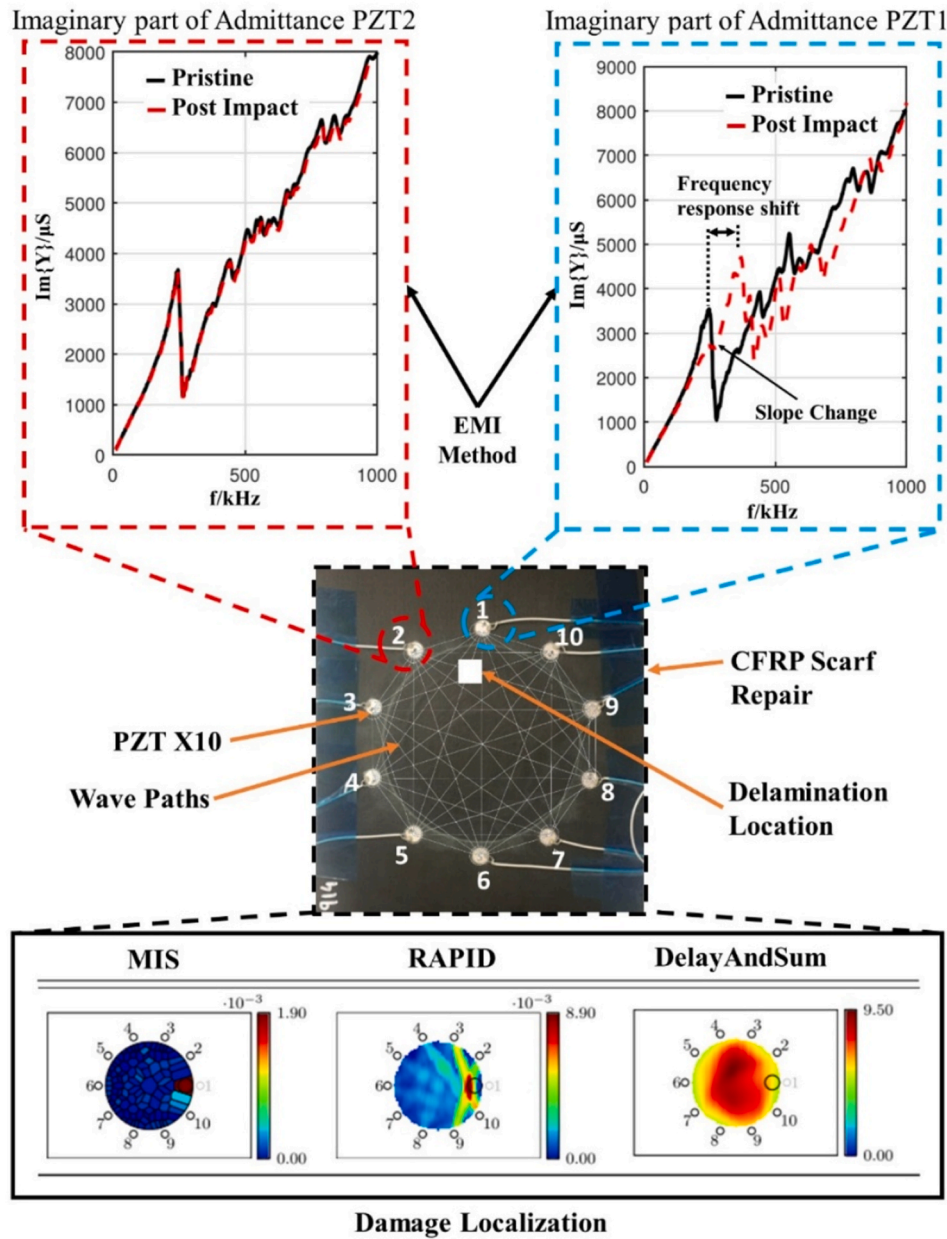


Fig. 17. Damage localization in bonded scarf panels using PZT arrays via EMI and guided waves (adapted from Ref. [228]).

conductive fillers, forming continuous pathways for charge transport. However, unlike bulk metals, where free electrons move through a uniform atomic lattice, the overall conductivity in such a system depends on the spatial distribution, connectivity, and contact resistance of the conductive fillers within the insulating matrix. Conductivity in such a system follows percolation theory as described by the Kirkpatrick and Zallen model [320], as shown in equation (2):

$$\sigma = \sigma_0 (X - X_c)^B \quad (2)$$

where σ is the electrical conductivity of the composite, σ_0 is the base electrical conductivity of the conductive phase, X is the volume fraction of conductive filler, X_c is the percolation threshold, and exponent B describes how sharply conductivity increases once X exceeds X_c , and it depends on the filler geometry, size distribution, shape [321]. The governing mechanism of charge transport in piezoresistive polymers depends primarily on the size of the conductive filler, which can be macro-scale particles, such as carbon fibers, or nanoscale particles, such as carbon nanotubes (CNTs) and silver nanoparticles. When macro-sized

fillers are considered, electrical transport is entirely governed by percolation theory, meaning that conduction occurs only when direct physical contact is established between adjacent conductive fillers [322, 323]. Mechanical strain alters resistance by disrupting or reconfiguring these conductive networks. Under tensile strain, fewer particles remain in contact, causing the conductive network to fragment, breaking interparticle connections and increasing resistance. Under compressive strain, the filler density increases, leading to enhanced connectivity and a corresponding decrease in resistance [324]. However, it is not practical to use macro-scale fillers in polymers for enhancing piezoresistivity, because their low aspect ratio means that a high filler concentration would be needed to establish percolation [325]. Taking CFRPs as an example, the characteristic resistance of carbon fibers can be used to check if fibers underwent breakage. However, they are ineffective in detecting early matrix cracking or microdamage, as these primarily occur within the resin, where percolation is absent due to the relatively large filler size [326]. When the size of conductive fillers is reduced to the nanoscale (i.e., at least one dimension between 1 and 100

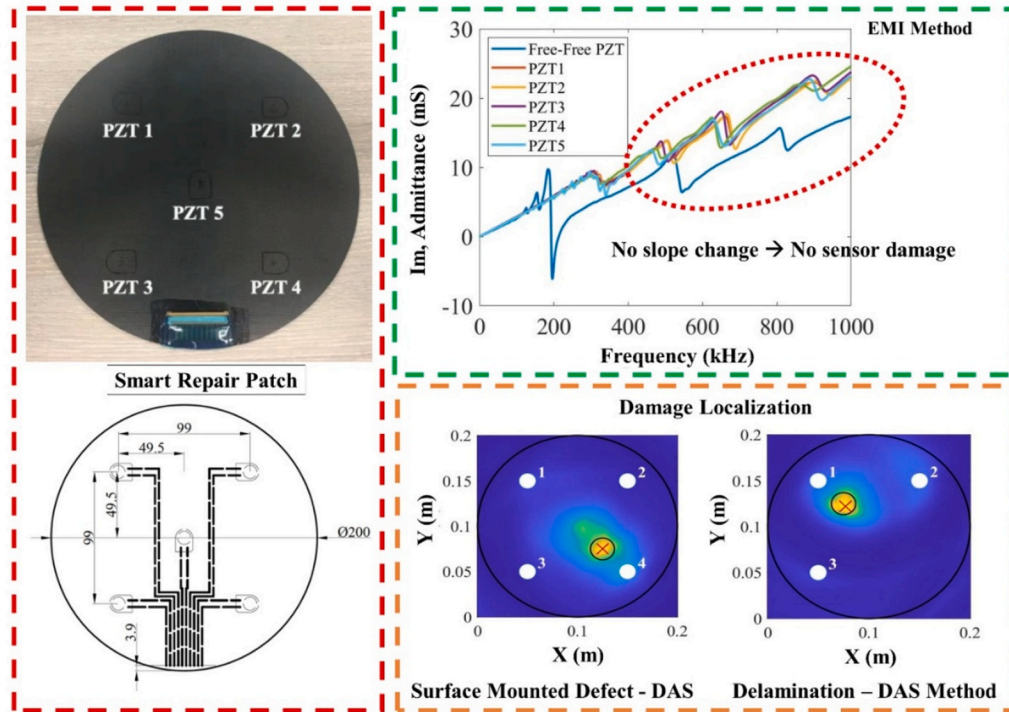


Fig. 18. Embedded PZT sensor network within a smart repair patch for damage localization in bonded repairs (adapted from Ref. [303]).

nm), an additional conduction mechanism called quantum tunneling emerges alongside percolation. Quantum tunneling occurs when the interparticle distance is reduced to the nanometer scale, typically below 10 nm, at which point electrons do not necessarily require sufficient classical energy to pass through the insulating polymer barrier but instead possess a finite probability of penetrating through it via quantum mechanical tunneling [320,327]. This tunneling process is well described by the Simmons model for electron tunneling across a thin insulating barrier [328]. In a simplified form [329], the tunneling resistance R_T is expressed in equation (3) as follow:

$$R_T \propto e^{2k_2 L} \quad (3)$$

Where L is the physical thickness of the insulating barrier (i.e., the gap between conductive fillers), and k_2 is the decay constant that quantifies how rapidly the electron's wavefunction decays inside the insulating barrier.

As tunneling probability decreases exponentially with increasing gap width, even very small changes in L lead to large variations in the resistance. For example, when tensile strain is applied, the fillers are forced further apart, reducing the tunneling probability and increasing the overall resistance. Conversely, compressive strain decreases the gap, enhancing tunneling and thereby lowering the resistance [330]. This mechanism is typically illustrated in schematic Fig. 19. Moreover, because the overall sensitivity of these nanocomposite strain sensors derives not only from the tunneling mechanism but also from alterations in the percolated conductive network, such materials rank among the most sensitive strain sensors available today, with gauge factors over 50 times greater than those of conventional metallic strain sensors [331, 332]. Nanofillers can exist in several structural forms, mainly classified based on their dimensionality [333], such as (i) 0D nanofillers: all dimensions are in the nanoscale, (ii) 1D nanofillers: one dimension extends beyond the nanoscale, and (iii) 2D nanofillers: two dimensions extend beyond the nanoscale. CNTs are one of the most common nanofillers that exist today. They are 1D structures that typically have diameters in the nanoscale and lengths up to the micron scale. Therefore, they are considered to have a high aspect ratio, which enhances

interparticle connectivity, increase the probability of quantum tunneling, and allows percolative networks to form at lower filler concentrations as low as 0.1 wt% [126,334,335]. CNTs can have three main forms, namely Single-Walled Nanotubes (SWNTs), which consist of a single rolled graphene sheet; Double-Walled Nanotubes (DWNTs), composed of two concentric graphene layers; and Multi-Walled Nanotubes (MWNTs), which contain three or more nested graphene layers. Typically, SWNTs exhibit superior mechanical strength, electrical conductivity, and thermal conductivity compared to MWNTs. However, SWNTs are more prone to synthesis defects due to their single-layered structure. In contrast, MWNTs offer greater structural robustness, as their multiple concentric layers provide a compensatory mechanism against structural defects [336,337].

One of the greatest advantages of PZR, such as CNT-based sensors, is the simplicity and efficiency of signal post-processing. This process relies on monitoring resistance changes between two electrodes or points using basic instruments such as multimeters. In the context of SHM and composite bonded repairs, CNTs can be utilized in two primary ways: (i) either by doping CNTs into the insulating adhesive layer to detect internal defects and cracks within the bond-line, thus allowing the entire adhesive joint to function as a sensor, or (ii) by fabricating CNT-based strain sensors, such as MXene or Buckypaper, which can be surface-mounted on the patch, parent structure, or patch-parent interface to monitor damage initiation and propagation.

4.2.1. CNTs as standalone sensors

Wang et al. [339] developed MXene-based sensors consisting of stacked 2D carbon nanosheets that form conductive pathways. In another work, the authors [229] developed Buckypaper (BP) sensors from homogeneously dispersed multi-walled carbon nanotubes (MWCNTs). The authors conducted separate studies to evaluate the effectiveness of MXene and BP sensors in detecting damage initiation and propagation. The sensors were bonded to three distinct locations on a bonded scarf-repaired CFRP panel: the bond-line interface, the proximal end, and the distal end of the patch repair, as shown in Fig. 20. During static tensile testing, resistance-displacement monitoring

revealed three key behaviors. Smooth, continuous resistance changes indicated minimal damage; drops or spikes signaled structural damage such as cracking or debonding, while oscillations reflected sensor failure preceding structural failure. When intact, resistance returned to its initial value upon unloading. Tracking resistance thus provided clear insight into damage initiation and progression, where it remained stable in undamaged states but increased with load once damage began. Under tensile fatigue, both sensors effectively captured stiffness degradation, crack initiation (indicated by a sudden resistance increase), and crack propagation or debonding (indicated by a steep rate of resistance change). These findings, validated by digital image correlation (DIC) and direct observation, confirmed high sensor stability and reliability in composite bonded repairs under operational loading. Moreover, the sensors demonstrated a high gauge factor (around 13), nearly seven times that of conventional strain gauges, indicating exceptional sensitivity for detecting microcracks and debonding. Nevertheless, the principal limitation is spatial, as each sensor measures only local strain perturbations and cannot independently localize damage, particularly when the damage does not significantly influence the surrounding strain field to reach adjacent sensors. Further studies are needed to evaluate the capability of these sensors to detect subsurface cracking within the repair structure. Overall, MXene and BP layers reliably transduced local network disruptions into diagnostic resistance signatures of damage evolution, though mapping the full extent requires complementary techniques.

4.2.2. CNTs as nanofillers in insulating polymers

Typically, CNTs are incorporated into adhesive films or polymeric matrices by dispersing them within the resin, often using an airbrush with a fixed stand-off distance and time. However, during dispersion, CNTs tend to agglomerate and entangle in localized regions, which can create stress concentration sites and negatively affect both the mechanical and electrical properties of the doped joint. To prevent this, the mixture is usually subjected to sonication (low-frequency ultrasound) or roll mills, often with the addition of surfactants to disentangle the CNTs and achieve a homogeneous distribution [340,341]. Nevertheless, a major concern with this method is the potential impact of CNT incorporation on the mechanical and electrical properties of the composite joint, as well as the sensitivity of the doped joint to process parameters such as sonication time and surfactant concentration. X.F. Sánchez-Romate et al. [342] investigated the influence of sonication time and surfactant content on the mechanical and electrical performance of CFRP joints bonded with CNT-doped epoxy film adhesive (FM 300K, 0.1 wt% CNTs). Lap shear tests assessed joint strength. As shown in Fig. 21a, increasing sonication reduced CNT entanglement and clustering, which otherwise generate stress concentrations and degrade

mechanical properties. However, excessive sonication led to CNT breakage, lowering conductivity by decreasing the aspect ratio and increasing the percolation threshold. The optimal sonication duration was 20 min. The authors also evaluated sodium dodecyl sulfate (SDS) concentrations (0–1 wt%) at this sonication time. Low SDS levels increased entanglement and reduced both electrical and mechanical properties, while excessive SDS over-dispersed CNTs, disrupting the conductive network and lowering conductivity. Moreover, SDS residues in the adhesive diminished lap shear strength (Fig. 21b). An optimum of 0.25 wt% SDS achieved uniform dispersion without property loss. Overall, the study underscored the need to optimize processing parameters to balance CNT dispersion, network integrity, SHM capability, and joint performance. X.F. Sánchez-Romate et al. [230] advance this research toward practical repair applications by doping FM 300 epoxy film with 0.1 wt% MWCNTs and applying it in a rectangular scarf repair on a CFRP panel to evaluate its ability to detect damage initiation and localization under shear loading. Complementary lap shear and double cantilever beam (DCB) tests on standard samples showed that shear strength and mode I fracture toughness were largely unaffected by CNT addition. This stability was attributed to the opposing effects of CNT-induced crack bridging, which enhances toughness, and the surfactant's influence, which slightly weakens bond-line adhesion. The repaired panel was instrumented with five electrodes and eight strain gauges attached to the top and bottom faces of the repaired panel, as shown in Fig. 22. Resistance changes recorded by the electrodes were validated using strain gauges, ultrasonic inspection, and acoustic emission. As the applied load increased, ultrasound imaging detected debonding near the upper corner (E1) and lower corner (E3), which corresponded to the highest variation in electrical resistance due to crack nucleation and subsequent debonding propagation that disrupted the CNT electrical pathways. Resistance peaks taken from E1 and E3 aligned well with ultrasound imaging results and acoustic emission signals at critical load levels recorded during testing.

Conversely, resistance changes in channels E4 and E5 were significantly lower than those in E1 and E3, and no apparent debonding was observed in the ultrasonic inspection images in those corners. However, strain gauge data showed significant deformation in these locations and correlated well with resistance change measurements. This behavior was attributed to adhesive deformation and microcracking, which exerted a lesser impact on the CNT network compared to debonding. Although this approach successfully enabled damage initiation detection and localization, the results demonstrated the high potential of the proposed CNT-doped adhesive film for bonded repair scenarios. Nevertheless, successful damage localization relied on comparing the highly varied resistance signals across the multiple, discretely placed channels (E1 to E5). This dependence means that channels registering

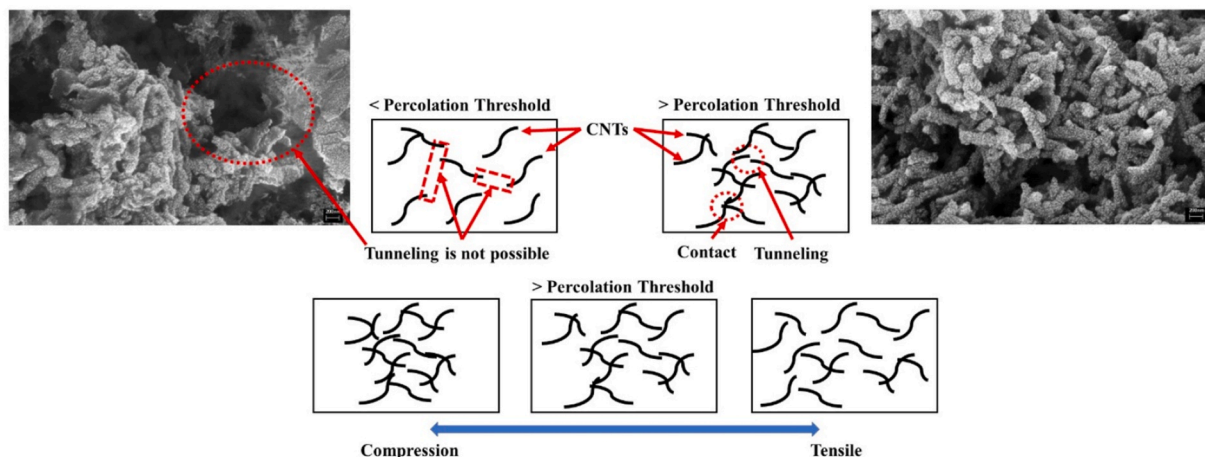


Fig. 19. Strain-sensing mechanisms in CNTs (SEM images source - [338]).

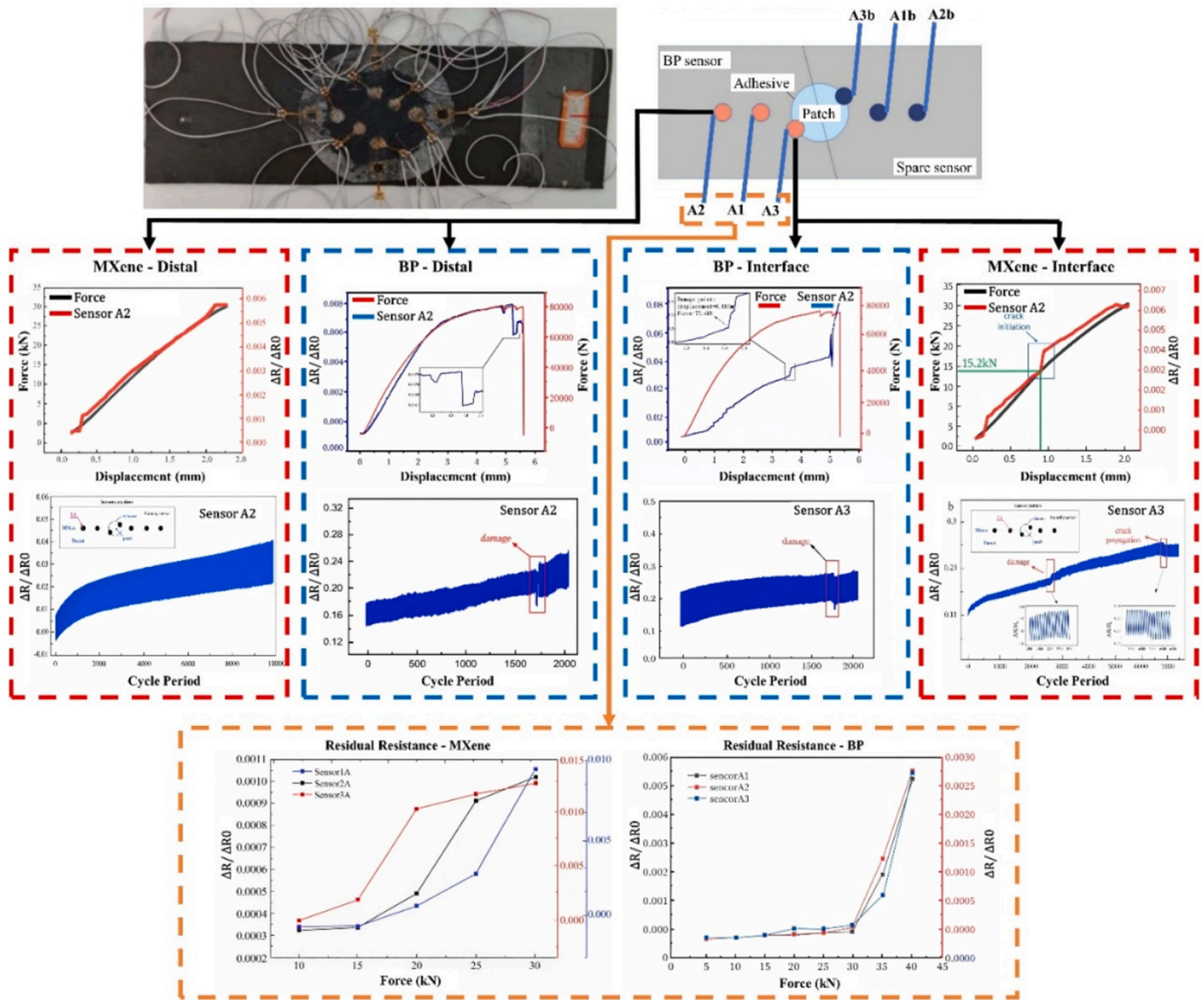


Fig. 20. Application and placement of standalone PZR (MXene and Buckypaper) for damage detection in composite scarf repairs (adapted from Refs. [229,339]).

only minor adhesive deformation (E4/E5) would fail to detect the severe, pathway-breaking debonding failure occurring in other locations (E1/E3), thus requiring obtaining measurements from multiple locations for accurate detection and pinpointing of damage. One way to improve damage localization accuracy is by employing arrays of conductive paths and measuring resistance changes across the network. These conductive paths can be deposited either on the surface of the patch/parent structure or embedded within the bond-line. In this context, conductive paths consist of conductive nanofillers, most commonly silver nanoparticles, dispersed in a solvent medium and mixed with a surfactant to minimize agglomeration. These three components form a conductive ink, which is then used in an inkjet printing process to deposit ink droplets onto the desired surface without the need for adhesives. Conductive pathways are then formed through a sintering process, during which the solvent evaporates and the silver nanoparticles bond together, creating a solid, continuous, and highly conductive path. To ensure proper electrical contact, wires are attached to the pathways using silver paint, which enhances adhesion and reduces contact resistance [343]. This method was implemented in repair scenarios by Augustin et al. [231], who printed silver nanoparticle-based conductive paths on the surface of a CFRP scarf joint,

as shown in Fig. 23. To ensure that electrical current flowed through the adhesive layer rather than the CFRP plate, the scarfed CFRP surfaces were electrically insulated before printing the conductive paths. Since the primary objective was to detect damage initiation and localization within the bond-line, the polymer itself needed to be conductive. Therefore, the polymer was doped with 0.1% SWCNTs to establish a conductive pathway along the entire bond-line; thus, the entire joint would act as a sensor. The scarf joint was subjected to tensile fatigue testing, during which electrical measurements were taken for all channels using copper wires connected to the silver paths. Throughout the fatigue test, localized strain regions along the bond-line were observed, as well as crack relocation and complete debonding.

These observations were visually confirmed and validated using DIC. The resistance change map across different channels effectively captured crack relocation and the location of debonding within an error margin of approximately 4 mm. The accuracy of this method can be further improved by increasing the number of conductive paths and reducing the spacing between them.

Compared with FOS and PZTs (Table 4), CNT-based piezoresistive sensing offers a fundamentally simpler, more sensitive, and more easily integrable approach to SHM of bonded repairs. It eliminates the need for

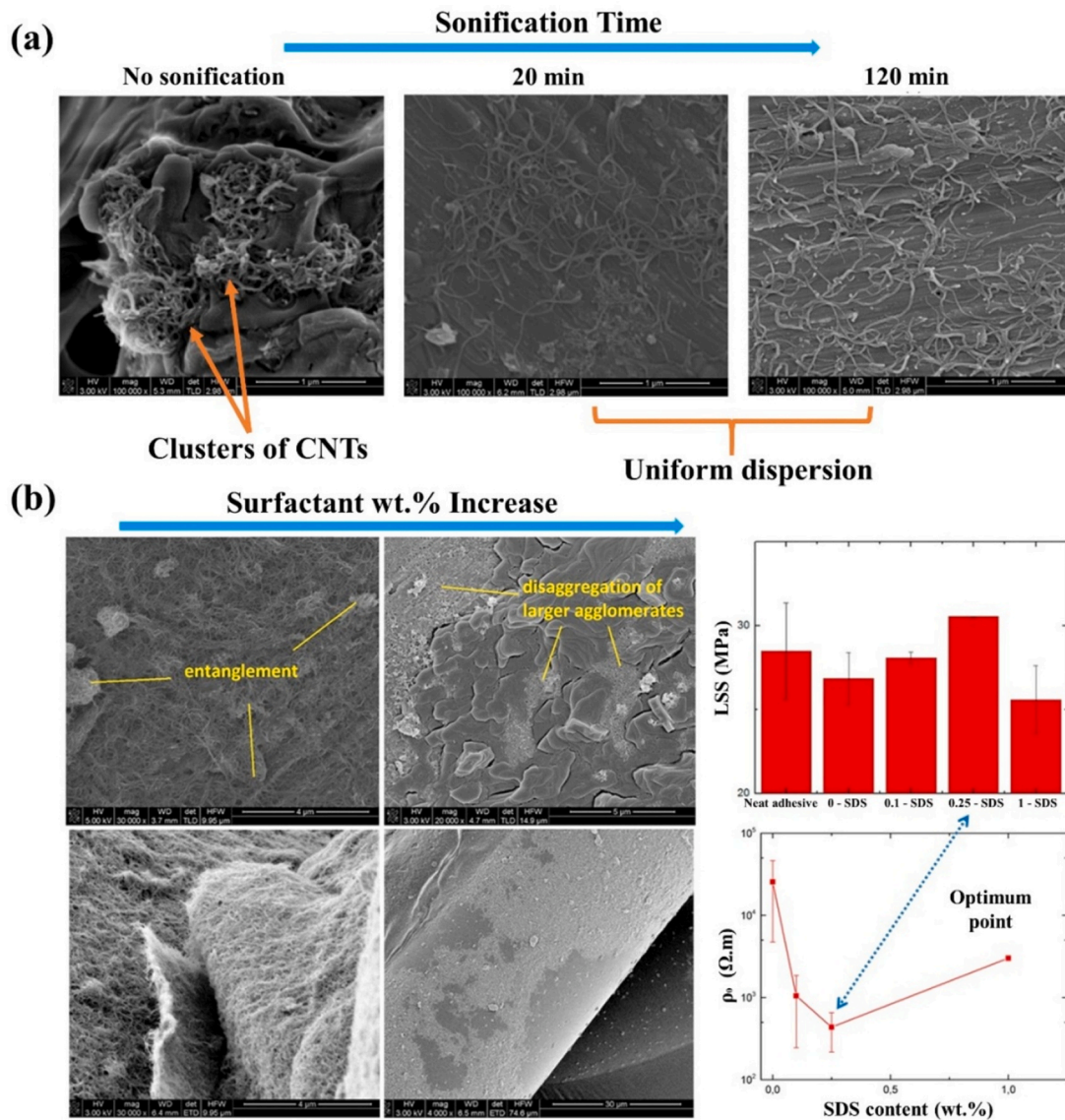


Fig. 21. Effect of (a) sonication time and (b) surfactant weight percentage on the performance of CNT-doped epoxy adhesive films (adapted from Ref. [342]).

complex and costly interrogation, relying solely on simple electrical resistance measurements. Exceptional gauge factors enable early detection of microcracking and debonding, while direct dispersion within the adhesive transforms the bond-line into a distributed sensor. This combination of high sensitivity, low complexity, and full bond-line integration provides a robust pathway toward certifiable bonded repairs in primary structures. However, a significant challenge with CNT-doped adhesive layers is the absence of a unique or proportional relationship between electrical resistance change and the actual type or extent of damage within the joint. As demonstrated by Shin and Chen [344], identical voltage variations recorded from CNT-modified carbon/epoxy lap joints corresponded to markedly different debonding areas and remaining fatigue lives. This inconsistency arises because multiple, coexisting mechanisms such as the loss of nanotube-nanotube contact, alteration of tunneling distances, internal piezoresistivity of CNTs, and reduction in conductive cross-section due to crack propagation, simultaneously influence the overall resistance response. Each mechanism evolves differently under tensile and cyclic fatigue loading, making it extremely difficult to isolate a single parameter that scales linearly with structural degradation. By contrast, FBG sensors are embedded along the longitudinal bond-line edges, where stress concentrations are highest, providing spatially resolved and mechanism-specific damage detection.

Using full-spectrum analysis, the authors employed a D-parameter to quantify spectral chirping caused by non-uniform strain redistribution. Minimal spectral change correlated with elastic response, while progressive broadening and intensity shifts corresponded to microcrack initiation, local debonding, and interfacial failure, verified by fluorescent penetrant imaging. The D-value is scaled with debonding depth, enabling reliable differentiation between early and advanced damage. Consequently, while CNT-based sensing effectively identifies the onset of damage, it lacks the capacity to quantify damage severity or differentiate between damage modes. Future research should aim to address how the various electromechanical mechanisms interact during damage evolution so that changes in resistance can be interpreted with greater confidence. Equally important is the need for consistent processing methods and long-term durability studies under realistic service conditions. Together, these efforts would help transform CNT-based sensing from a promising early-warning tool into a dependable and interpretable SHM approach for certifiable composite bonded structures.

Despite the proven capability of the three main SHM sensing technologies to detect the initiation, propagation, and location of damage, which can be regarded as the fundamental pillars upon which SHM in the context of bonded repairs stands, the integrity and long-term durability of composite bonded repairs are primarily governed by two critical

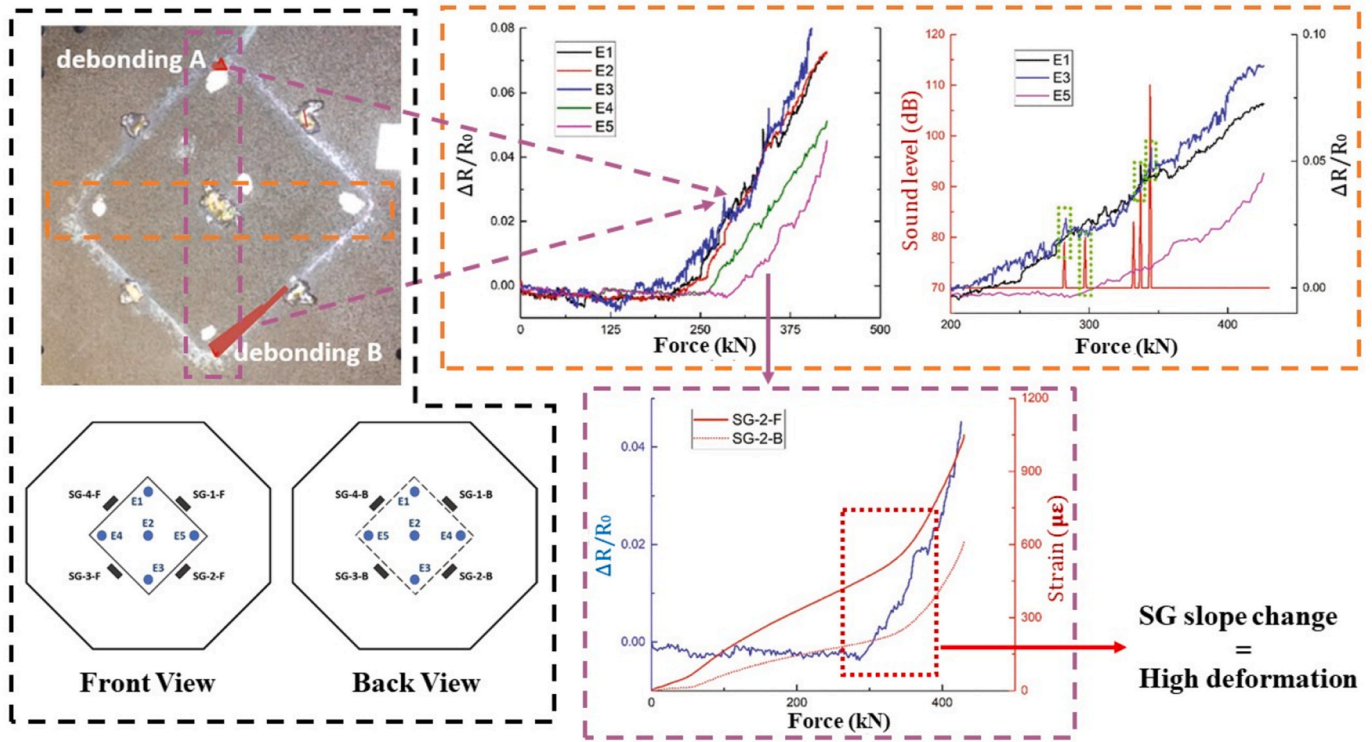


Fig. 22. Correlation of resistance changes, ultrasound, and acoustic emission for damage detection in CNT-Doped adhesive joints (adapted from Ref. [230]).

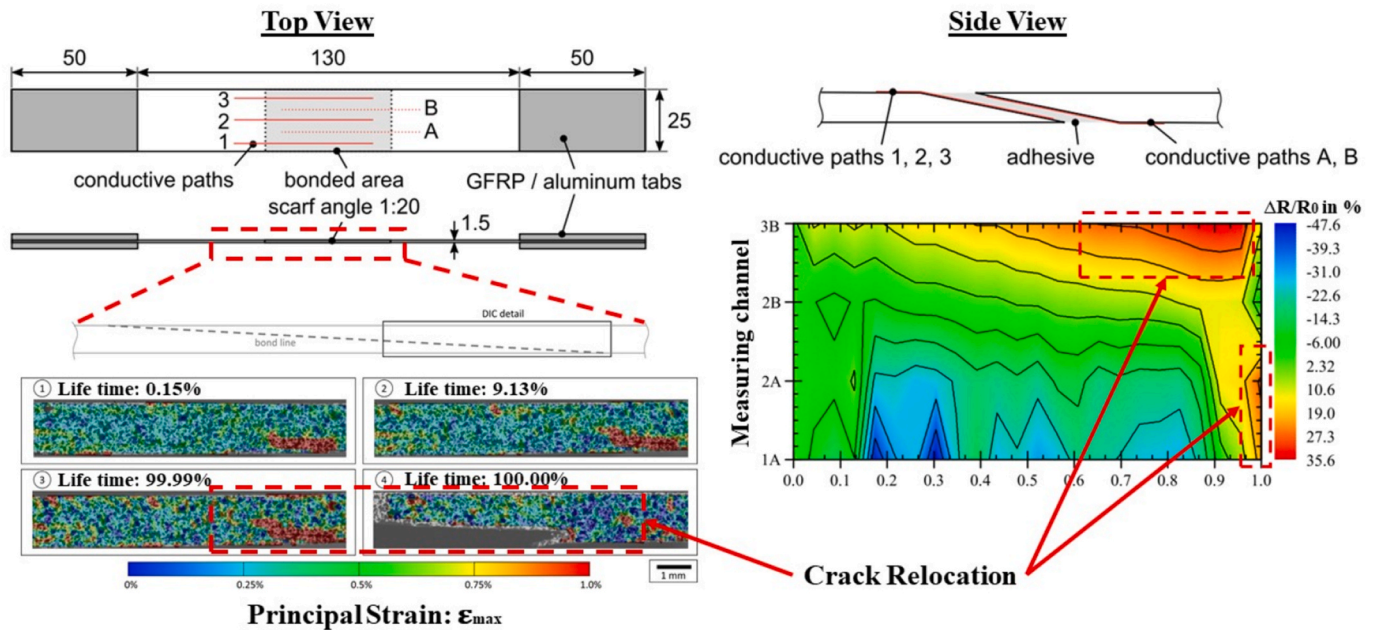


Fig. 23. Damage detection and localization in CFRP scarf joints using printed silver nanoparticle conductive paths and CNT-doped adhesive film (adapted from Ref. [231]).

factors: (i) the degree of adhesive cure and (ii) the magnitude of residual stresses generated during the manufacturing process. Evaluating the quality of both factors before releasing the bonded structure into service is arguably the most important step in any structural health monitoring application. The degree of cure determines the development of the adhesive's mechanical and thermal properties, directly influencing bond strength, stiffness, and long-term performance. Incomplete or nonuniform curing can result in weak interfacial adhesion, reduced load

transfer efficiency, and premature failure under service conditions [345, 346]. Moreover, residual stresses arise from differential thermal expansion, curing shrinkage, and mechanical constraints between the adherend layers and between the adherends and the adhesive layer. Excessive residual stresses can cause microcracking, delamination, a reduction in joint strength, and accelerated damage initiation and growth [347–349]. Therefore, real-time monitoring of both parameters during repair fabrication is essential to ensure optimal curing

Table 4

Comparative analysis of SHM technologies for composite bonded repairs: FOS, PZT, and PZR/CNTs.

Feature	Fiber Optic Sensors (FOS)	Piezoelectric Transducers (PZT)	Piezoresistive Sensors (PZR)/CNTs
Main Sensing Principle	Modulation of light properties (intensity, phase, wavelength) by external physical parameters like strain or temperature.	Piezoelectric effect (mechanical stress $\leftrightarrow$ electrical charge). Used in active (EMI, UGW) and passive modes.	Piezoresistive effect (change in electrical resistance due to stress/strain). Conduction via percolation and quantum tunneling.
Initial damage Detection	High capability. Detects damage through multiple methods such as changes in strain ratio or spectral distortion, reflecting loss of load transfer, or changes in micro-strain.	High capability. EMI tracks electrical impedance changes due to local mechanical impedance alterations. UGW tracks changes in wave characteristics (amplitude, ToF).	Exceptional capability. Measures of electrical resistance changes caused by microcracking or debonding, disrupting the conductive network.
Damage Propagation Detection	Capable. Tracks crack front movement (DFOS/OBR), spectral changes (CFBG), or transition to nonlinear/chaotic vibration signatures during fatigue.	Capable. UGW methods (e.g., analyzing peak attenuation or using damage indices) show good correlation with propagation route and expected developed internal damage.	Excellent capability. Resistance reliably increases with applied load once damage initiates, indicating progressive damage accumulation.
Damage Localization Detection	High localization potential using DFOS. OBR/SWI provides continuous, high-spatial-resolution strain data over the entire joint length. FBGs require arrays/multiplexing.	High localization potential using arrays. UGW algorithms (MIS, DAS, RAPID) utilize PZT arrays to calculate propagation path differences and map damage location. EMI is limited to local damage detection.	High Potential using multiple conductive arrays/electrodes. Successful localization relies on comparing highly varied resistance signals across multiple, discretely placed channels or conductive paths (e.g., printed silver nanoparticle paths).
Signal Processing and Acquisition Complexity	High complexity and cost. Requires specialized optical interrogation systems. Signal processing needs algorithms for cross-sensitivity compensation (strain/temperature).	Highly complex. Data processing for Lamb waves is complicated by wave dispersion (wave speed varies with frequency). Requires advanced signal processing and compensation algorithms for external factors (temperature, vibration).	Minimal complexity. Relies solely on monitoring simple electrical resistance changes between electrodes using basic instruments (e.g., multimeters).
Suitability for Integration with bonded repairs	Suitable for surface attachment, embedment inside composite adherends (patch layers), and embedment inside the adhesive bond-line.	Most suitable for surface-bonding (outside repair area). It can be embedded within the composite patch, but extra measures shall be taken due to the high risk of short-circuiting.	Excellent for bond-line integration. Nanofillers can be dispersed directly into the adhesive film, turning the entire adhesive joint into a distributed sensor. Standalone sensors (MXene/BP) are suitable for surface attachment. Integration inside the composite adherends requires further investigations.
Link to damage modes	provide clear, spatially resolved strain signatures that can be correlated with both the type and severity of damage	The mapping between this generic index and actual damage size or specific mode is less direct, and this correlation remains largely unvalidated under simultaneous mechanical loading in repair scenarios.	Lack of a reliable, proportional link between resistance change and actual damage severity or mode
Ability for adhesive cure monitoring	FBG and DFOS are highly suitable for quantifying thermo-mechanical strain induced by resin shrinkage and thermal mismatch, and thus inferring the degree of cure	PZT sensors can detect the level of adhesive cure by utilizing the Electromechanical Impedance (EMI) method.	CNT-based sensors and nanocomposite films show promise for monitoring cure progression. They can monitor the level of adhesive cure through distinct, reproducible resistance changes that correspond to resin infiltration, viscosity evolution, crosslinking, and gelation during cure.
Ability to quantify residual stresses	FOS technology is the only well-established sensor technology that can be embedded between composite adherends and inside the bond-line while also quantifying residual stresses during fabrication.	PZTs fundamentally cannot measure residual stress since they generate charge only during stress changes, not under static conditions. Residual stresses are static internal forces, and PZT output decays to zero due to electrical leakage, rendering sustained static output impossible.	CNT-based systems are not yet validated for quantitative residual stress mapping in absolute terms, because their electrical response is influenced by multiple coupled factors (such as thermal expansion and chemical crosslinking), making it difficult to isolate the purely mechanical component of resistance change.
Main Advantages	Immunity to electromagnetic interference, lightweight, long operational lifespan (up to 20 years), and low power consumption. DFOS offers continuous sensing over large areas.	Functions as both an actuator and a sensor. UGW allows for global monitoring due to low energy attenuation and long propagation range. EMI effectively detects localized damage, like transducer bonding quality.	Superior simplicity and efficiency of signal post-processing. Exceptional sensitivity (Gauge Factors >50 times the conventional metallic strain sensors). Nanofillers allow the entire adhesive bond-line to function as a distributed sensor.
Main Limitations	High complexity/cost of interrogation systems. Cross-sensitivity (strain/temperature) requires compensation. Fragility under mechanical stress. Embedding (diameter $\approx$ 125–130 μ m) introduces defects. Primarily sensitive to longitudinal strain, constraining placement.	Requires significant energy consumption for active, real-time monitoring. Wave dispersion complicates damage identification. Embedding is challenging due to short-circuiting risk from carbon fibers and the required wiring/shielding bulk. Few studies exist on localization under simultaneous mechanical loading.	Localization requires comparison of signals across multiple, discretely placed channels, which must register pathway-breaking damage to be effective. Standalone sensors only measure local perturbations. Requires careful optimization of processing parameters (e.g., sonication, surfactant ratio) to maintain properties. Lacks quantitative correlation to damage size/severity.

conditions, minimize internal stress accumulation, reduce repair rejection risk, and accurately assess repair quality before returning the structure to service. Although the three SHM sensing technologies have been proven suitable for damage detection, all can be used to detect the degree of cure, but not all can detect residual stress. FBGs and DFOS are among the most validated approaches for concurrent cure and strain monitoring in bonded joints. They can accurately track the strain history of the adhesive during curing and thereby infer both the degree of cure and residual strain accumulation. For example, Shin and Chen [350] reported that Fiber Bragg Gratings embedded in adhesive joints reliably

reflect strain as curing progresses. By recording Bragg wavelength shifts, these sensors capture the thermomechanical strain induced by resin shrinkage and thermal mismatch. DFOS can similarly provide a spatial strain profile along the bond-line. Additionally, many studies have shown the capability of FOS for monitoring residual stress during the cure of composite laminates. However, the accuracy of residual stress or strain measurement is significantly affected by the placement of the FOS, particularly its depth and orientation. Yadav et al. [351] demonstrated that FBG embedded between the second and third plies in a fifteen-ply composite laminate during the automated fiber placement

process could only measure the residual stresses and strains in the nearby plies, but not in the far ones. Consequently, other studies have positioned multiple FOS at different layers to capture residual strains across the thickness [352]. Additionally, slight misplacement or poor adhesive coupling of the fiber can be expected to blur or distort the readings. By contrast, piezoelectric sensors can detect the level of adhesive cure by means of the EMI method [353]. However, piezoelectric sensors cannot measure residual stress, as they generate an electrical charge only during dynamic stress changes, not under static conditions. As clarified by Sirohi and Chopra [354], these sensors experience electrical leakage, which makes sustained static output impossible. The generated charge eventually dissipates, making it impossible to determine a purely static condition. Because residual stresses are static and represent unchanging internal forces locked within a material after manufacturing, PZTs do not produce a useable signal for such measurements. Even in quasi-static conditions, such as slow adhesive curing where residual stress evolves gradually, the sensor output decays to zero faster than the stress changes occur due to charge leakage. CNT-based sensors and nanocomposite films have also shown promise for monitoring cure progression and detecting stress evolution within adhesive layers. Rodríguez-Uicab et al. [355] demonstrated that a single carbon nanotube yarn embedded in an epoxy matrix exhibits distinct, reproducible resistance changes corresponding to resin infiltration, viscosity evolution, crosslinking, and gelation during curing. These electrical responses arise from changes in nanotube contact and network connectivity as the polymer densifies and curing-induced stresses develop. However, CNT-based systems are not yet reliable for quantitative residual stress mapping in absolute terms, as their electrical response is affected by multiple interacting factors such as resin infiltration, charge transfer dynamics, thermal expansion, and chemical crosslinking, making it difficult to isolate the purely mechanical component of the resistance change [356–358]. Therefore, based on the assessment of structural health monitoring technologies, it can be concluded that no single technique provides a comprehensive solution. Future research should therefore focus on developing hybrid approaches to achieve reliable and integrated monitoring of repair processes, thereby paving the way toward the certification of bonded repairs.

5. Conclusions

This review provides an in-depth review of the recent advances in composite repair using conventional and non-conventional machining processes for damage removal. In this regard, the added value of using the abrasive water jet machining (AWJM) process for damage removal and surface preparation was discussed in detail in comparison to the conventional machining (CM) methods traditionally used in aerospace composite repair. The paper also offers a comprehensive overview of structural health monitoring (SHM) techniques applied to composite bonded repairs through various sensor technologies, evaluating their effectiveness in enabling continuous, in-service monitoring of bond integrity. The main conclusions can be summarized as follows:

1. CM (Conventional machining) processes, commonly employed in aeronautical composite repair, introduce significant surface and subsurface defects that compromise bond quality and repeatability. Processes such as milling and grinding are labor-intensive and often result in defects, including matrix cracking, resin smearing, delamination, and heat-affected zones (HAZs). These defects act as non-uniform stress concentrators, degrading adhesion quality and thereby reducing the overall structural capacity while increasing repair rejection rates. Additionally, CM techniques struggle to achieve the high-dimensional precision required for structural repair geometries, such as scarf and stepped-lap joints, particularly when performing ply-by-ply removal on composite components. This process can disrupt the layer symmetry of composites, and the high cutting forces associated with CM induce coupled bending-extension and torsional loads, leading to unpredictable material removal and geometric distortion.
2. AWJM (Abrasive Water Jet Machining) provides a practical alternative as a cold, erosive material removal process that mitigates thermal damage and eliminates the heat-affected zones (HAZs) commonly induced by CM. It enables significantly greater control over defect generation and surface morphology, producing uniformly distributed surface features, such as craters and streaks, that are largely independent of the composite stacking sequence or fiber orientation, unlike CM. Moreover, AWJM allows precise, orientation-insensitive ply-by-ply removal by operating with minimal cutting forces (in the single-digit Newton range), compared to the hundreds of Newtons typical of CM. This substantially reduces part deformation during the machining of composite laminates. In addition, AWJM offers a unique industrial advantage by combining damage removal and surface preparation into a single, streamlined operation. AWJM-induced surface texturing has been shown to significantly enhance adhesive bonding performance, with reported increases of up to 49% in mode-I fracture toughness and approximately 40% in shear strength compared to conventional surface treatments such as sandblasting. Furthermore, predictive modeling approaches employing 3D surface metrics, such as crater volume (C_v) and arithmetic mean height (S_a), enable the objective engineering of optimal, bond-critical surface morphologies. This represents a significant technical advancement toward more accurate predictions of bond-line performance.
3. The manual nature of composite bonded repair, combined with the unique requirements of each step in terms of operator skill and tooling, often leads to the formation of multiple and distinct defect types that can impair the long-term performance of bonded structures. Currently, there is no single non-destructive testing (NDT) technique capable of detecting all forms of damage in composite bonded repairs, such as kissing bonds. Moreover, existing NDT methods are generally not designed to evaluate bond quality or repair strength without the use of destructive testing. Therefore, adhesively bonded repairs do not fully satisfy current safety regulations and exhibit a degree of uncertainty, particularly with respect to long-term structural reliability. Repair-induced defects may propagate unpredictably, potentially leading to catastrophic failures. For these reasons, regulatory authorities such as the Federal Aviation Administration (FAA) restrict the application of adhesive bonding repairs to non-primary composite components, limiting their broader adoption in critical aerospace structures. A promising approach to overcoming these limitations is the implementation of Structural Health Monitoring (SHM) technologies. SHM enables both the assessment of bond-line integrity and continuous, real-time tracking of the performance of repaired components through the integration of sensors within the repaired part, either embedded in the bond-line, attached to the repair surface, or incorporated within the composite laminate itself. Three main SHM technologies are commonly employed in composite bonded repairs, namely:
 - a Fiber Optic Sensors (FOS) operate by converting strain- or temperature-induced variations in the optical field into measurable wavelength or backscatter shifts. In bonded repairs, they are typically surface-bonded along the adherend or embedded along the bond-line, and in some cases, they may be embedded between composite plies. This configuration enables either point-based (FBG) or fully distributed (DFOS) strain mapping. FOS has demonstrated the capability to detect changes in load transfer, identify early microcracking, monitor crack propagation through evolving strain gradients, and capture cure-related as well as residual-strain states with high precision. Their damage localization capability is strongest when using DFOS due to its sub-millimeter spatial resolution, whereas FBG arrays can only provide localization when sensor multiplexing is applied. However, their performance is limited by strain-temperature cross-

sensitivity, orientation-dependent strain transfer, and the potential formation of local resin-rich zones during embedding. Furthermore, there remains limited validation of FOS technology for real-time monitoring in complex repair geometries under multiaxial loading, as well as challenges related to the high complexity and cost of the specialized optical interrogation equipment required for data acquisition.

- b Piezoelectric Sensors (PZT) operate based on the direct and inverse piezoelectric effects, enabling both the excitation and sensing of guided waves or local impedance signals for damage detection. In composite repairs, thin PZT sensors are typically bonded around the repair zone to form pitch-catch networks for Lamb-wave interrogation or used individually in electromechanical impedance (EMI) mode to assess local stiffness and monitor the curing process. These sensors have been shown to detect adhesive defects, delamination onset, debond growth, and variations in local mechanical impedance. When combined with multi-path networks and algorithms such as MIS, DAS, RAPID, or DPIU, PZT systems can achieve highly accurate damage localization and effectively track propagation across the repaired component. However, accurate localization requires a large number of PZTs, and the number of sensors must increase with repair size. Damage to any single sensor within the PZT network may compromise overall localization capability. Moreover, because PZTs are most often surface-mounted, they are more susceptible to damage compared to sensors that can be embedded within the repair structure. Their performance is further affected by the complexity of signal processing, which is challenged by wave dispersion (where wave speed varies with frequency), and by external factors such as temperature and vibration that necessitate advanced compensation algorithms. Additionally, PZTs are incapable of measuring static residual stresses, as they continuously dissipate charge, making sustained static output impossible.
 - c Piezoresistive Sensors (PZR), such as those based on carbon nanotubes (CNTs), rely on electrically conductive nanofiller networks whose resistance changes when strain, microcracking, or debonding alters the percolation network and quantum tunneling paths. In bonded repairs, CNTs can be directly dispersed within the insulating adhesive film, effectively transforming the entire bond joint into a distributed sensor, or fabricated as standalone sensing elements (e.g., Buckypaper) for surface attachment. These sensors exhibit exceptional capability for early damage detection due to their high sensitivity (gauge factors exceeding 50 times those of metallic sensors), identifying microcracking or debonding through resistance increases that disrupt the conductive network. They can reliably track progressive damage accumulation and offer high localization potential by comparing resistance signals across multiple, discretely placed conductive paths or channels. PZR systems operate through simple electrical resistance measurements, enabling low system complexity and efficient signal acquisition and post-processing. The primary limitation lies in the absence of a reliable, proportional relationship between changes in electrical resistance and the quantitative severity or specific mode of structural damage. Unlike FOS or PZT systems, which can produce mode- or strain-dependent signatures that scale with crack growth or stiffness loss, PZR resistance variations are influenced by multiple overlapping mechanisms, hindering proportional or damage-specific interpretation. Moreover, PZR systems have not yet been validated for quantitative residual stress mapping in absolute terms and require careful optimization of processing parameters (e.g., sonication time and surfactant concentration) to maintain both network integrity and mechanical performance.
4. Achieving certifiable and durable bonded repairs in primary structures requires the functional integration and standardization of AWJM and SHM technologies. Future research must prioritize

establishing robust, long-term correlations between the AWJM-generated surface morphology and critical mechanical performance metrics, such as fatigue life, across diverse material systems and joint configurations. A critical prerequisite for this is the standardization of AWJM process parameters and the development of universal surface quality metrics, which will ensure repeatable and predictable bond performance. Concurrently, the operational stability, reliability, and precision of integrated SHM systems must be validated under realistic, combined environmental (e.g., thermal cycling, humidity) and mechanical loading conditions. This validation requires reporting objective performance indicators, including the probability of detection, localization error, and false-alarm rates, under equivalent service hours. Given that no single sensor technology offers a comprehensive assessment of repair quality, the deployment of hybrid SHM systems is an essential next step. The ultimate objective is the creation of an automated repair workflow that seamlessly couples AWJM material removal and surface preparation with smart sensing technologies. This integration will generate the traceable, high-fidelity data necessary to move composite bonded repairs beyond non-primary structures toward certification for primary load-bearing components. This integrated approach is the foundation for developing digital-twin models of bonded repairs, enabling sophisticated estimation of remaining useful life and supporting a transition from corrective to predictive maintenance practices.

CRedit authorship contribution statement

Atef Sawalmeh: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Redouane Zitoune:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Laurent Crouzeix:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Pablo Navarro:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Steven Marguet:** Writing – review & editing, Supervision, Resources, Conceptualization. **Arjun Chandra Shekar:** Writing – review & editing. **Lucas A. Hof:** Writing – review & editing. **Luiz Villa:** Writing – review & editing, Supervision. **Khaled Giasin:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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