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Bonded repair of composite aircraft structures: A review of scientific challenges and opportunities

K.B. Katnam [a,*], L.F.M. Da Silva [b], T.M. Young [a]

[a] *Irish Centre for Composites Research (IComp), Materials and Surface Science Institute (MSSI), University of Limerick, Limerick, Ireland*
[b] *Department of Mechanical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

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ABSTRACT

Advanced composite materials have gained popularity in high-performance structural designs such as aerospace applications that require lightweight components with superior mechanical properties in order to perform in demanding service conditions as well as provide energy efficiency. However, one of the major challenges that the aerospace industry faces with advanced composites – because of their inherent complex damage behaviour – is structural repair. Composite materials are primarily damaged by mechanical loads and/or environmental conditions. If material damage is not extensive, structural repair is the only feasible solution as replacing the entire component is not cost-effective in many cases. Bonded composite repairs (*e.g.* scarf patches) are generally preferred as they provide enhanced stress transfer mechanisms, joint efficiencies and aerodynamic performance. With an increased usage of advanced composites in primary and secondary aerospace structural components, it is thus essential to have robust, reliable and repeatable structural bonded repair procedures to restore damaged composite components. But structural bonded repairs, especially with primary structures, pose several scientific challenges with the current existing repair technologies. In this regard, the area of structural bonded repair of composites is broadly reviewed – starting from damage assessment to automation – to identify current scientific challenges and future opportunities.

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[*] Corresponding author: Tel: +353 61 202253.
E-mail address: kali-babu.katnam@ul.ie (K.B. Katnam).

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1. Composite materials: Aerospace industry

It is now scientifically and politically acknowledged that greenhouse gas emissions from different industries have been contributing to climate change [1,2]. Aircraft-engine emissions (*e.g.* carbon dioxide, nitrogen oxides, sulphur oxides *etc.*) are similar to other emissions resulting from fuel combustion, and contribute significantly to global climate change [3]. Aircraft emissions are emitted directly into the upper troposphere and lower stratosphere and thus have an impact on atmospheric composition, which makes them particularly potent compared to other emissions [4]. The formation of condensation trails (formed by the mixing of hot, moist air coming out of the engine with cold ambient air) in the wake of the aircraft has a warming effect on climate [5]. To combat the environmental threat that aviation industry poses, while agencies such as International Civil Aviation Organisation (ICAO) are working on international policies, the aerospace industry is aiming to considerably reduce emissions through weight reduction, aerodynamic improvements and new aircraft concepts [6,7]. For significant weight reduction, the application of composite materials in aircraft design is globally considered as one of the key technologies to meet emission targets.

Advanced composite materials, which are usually continuous carbon fibres with a polymer matrix for aerospace applications, can provide superior material properties than metals and thus enable lighter structural designs to be achieved [8]. The lighter structures result in lower fuel consumption and thus reduced emissions. Composite materials were first employed in military aircraft in the 1960s and later extended to civil aircraft applications in the 1970s [9]. However, civil aircraft manufacturers were slower to utilise composites in primary structural applications until the 2000s [10]. Now, as leading aircraft manufacturers replace traditional materials with advanced composite materials, the full potential of composites can be exploited through novel structural designs. Carbon-reinforced polymer composites are currently being used in aircraft design for primary and secondary structural applications. In recent years, advanced composites have been replacing traditional structural materials in primary load carrying aircraft structures to a significant extent (*e.g.* in the Boeing 787, approximately 50% advanced composites by weight) [11]. Similarly, the designs of the Airbus A350 and Bombardier CSeries, both currently under development, are using significant amounts of advanced composites. In addition to the improvement in fuel-efficiency and emission reduction, composite materials in aircraft design also improve passenger comfort. Composite fuselage, having higher allowable hoop stresses and corrosion resistance, would allow more comfortable levels of cabin pressure and humidity.

Carbon-fibre composites are usually manufactured in laminate or sandwich forms for aerospace structural applications [12]. Thermosetting (*e.g.* epoxies) or thermoplastic (*e.g.* poly-ether-ether-ketone) resins are often used as matrix material to hold reinforcing fibres. While the two matrix-material types have their pros and cons, thermosetting resins are currently extensively used in aircraft manufacturing [13] because of relatively low material and processing costs involved. The conventional manufacturing processes are based on the pre-preg approach (*i.e.* uni-directional fibres with pre-impregnated resin). However, as composite manufacturing using pre-preg materials is often expensive, alternative forms of materials and manufacturing methods are being sought to produce composites at a reduced cost [14]. For affordability and cost-efficiency, novel material (*e.g.* new fibre precursors [15], resin chemistries [16]) and manufacturing techniques (*e.g.* resin infusion of fibre pre-forms [17,18] for thermosetting resins, automated tape laying [19] for thermoplastics) are gaining popularity.

From a structural design viewpoint [20], carbon-fibre composites have many advantages such as high strength-to-weight ratio, high stiffness-to-weight ratio, improved fatigue tolerance, corrosion resistance, formability (*i.e.* easily mouldable to complex shapes), tailored mechanical properties, and low thermal expansion. On the other hand, from a structural affordability and safety viewpoint [21,22], some of the major challenges for the composites industry are: (a) reducing material and manufacturing costs, (b) ensuring manufacturing quality (*i.e.* repeatable and defect-free processes), (c) developing efficient joining technologies, (d) preventing in-service damage, (e) developing reliable design rules, and (f) improving structural maintenance and repair technologies. To overcome these challenges, research and development in composite materials have globally received significant attention in academic and industrial research centres.

2. Structural safety

2.1. Composite materials: Failure behaviour

Structural design rules for advanced composites, in comparison to metallic materials, are not yet mature [23]. As a fibre-reinforced composite material is a micro-structure in itself, with several carbon fibres (5–10 μm in diameter) held together by a polymer material, the mechanical properties of the fibre, matrix and fibre-matrix interface mainly contribute to the composite properties and failure mechanisms [22]. A weak fibre-matrix interface can lead to a low stiffness and strength but high resistance to fracture, whereas a strong interface produces high stiffness and strength but often a low resistance to fracture [9]. The failure behaviour depends not only on inherent heterogeneity and anisotropy, but also on possible failure modes and their interactions [24,25]. This complex failure behaviour is a major issue associated with the development of a robust failure criterion that incorporates all possible failure mechanisms with accuracy [26]. In addition, the new manufacturing processes often lead to a more complicated micro-structure (*e.g.* incorporating complex fibre architectures) and thus introduce complex failure behaviour [27]. It is worth noting that the failure behaviour of composite materials strongly depends on strain-rates as well as environmental conditions [28,29].

Damage in composite laminates can be at a lamina-scale (*i.e.* matrix-cracking, fibre-matrix debonding, fibre-brakeage), laminate-scale (*i.e.* delamination) or structural-scale (*i.e.* extensive component damage), which can occur due to mechanical and environmental conditions during service. Importantly, impact loads often induce considerable subsurface damage (*i.e.* at intra-lamina and inter-lamina levels) in composite laminates, with very limited visible surface damage. It is thus very important to consider different length scales (*i.e.* intra-lamina, inter-lamina, laminate, and component levels) in the analysis and design of composite structures [30]. Understanding the failure mechanisms and their interactions at each length scale is critical for the development of robust design rules [31].

2.2. *Industry concerns*

While composites are currently being used in both secondary and primary structural components, some industry observers have raised concerns about the rapid expansion in the use of composites in commercial aircraft and the preparedness of authorities such as the Federal Aviation Administration (FAA) for this transition. In a recent report, the US Government Accountability Office [32] identified several important aviation safety-related issues and categorised them into four areas: (a) limited information on the behaviour of composite structures, (b) technical concerns related to the unique properties of composite materials, (c) limited standardization of composite materials and repair techniques, and (d) level of training and awareness on composite materials.

Although the demand for composite products and components is globally growing at a healthy rate [33], the science and technology that support this growth needs to progress at a similar rate, which is lagging behind at the moment, for sustainability. In this regard, with immature design rules, manufacturing processes and joining technologies, the safety and efficiency of composite aircraft will largely depend on structural maintenance and repair [34]. With the increased usage of advanced composites in different structural applications, the demand for cost-effective and novel manufacturing processes (*e.g.* out-of-autoclave techniques, integrated structures) has also increased. This trend can lead to manufacturing defects and structural maintenance issues, which subsequently demands advanced repair techniques. While composite research and development activities are in progress globally, what the aerospace industry currently needs is a reliable technology for the maintenance and repair for primary and secondary structures [35].

3. Structural composite repair

3.1. *Structural inspection*

Aircraft structures require regular inspections (with procedures established by the aircraft manufacturers and airworthiness authorities such as the Federal Aviation Administration and the European Aviation Safety Agency) to ensure structural integrity, efficiency and safety [36]. The continued airworthiness of aircraft composite structures depends on several factors (*e.g.* impact damage, delamination, debonding, manufacturing defects). During service, structural damage can initiate from manufacturing defects (*e.g.* voids, weak bonds) or occur due to mechanical loads (*e.g.* impact) and/or environmental exposure (*e.g.* moisture, temperature) [37]. The residual strength of damaged composite components depends on the extent and nature of the damage. Damage caused by impact (*e.g.* dropped tools, service collisions, bird strike) can often be a critical threat to structural integrity [38]. Damage can also result from environmental factors such as moisture ingression, rain erosion, hail, lightning strike, ultraviolet radiation *etc*. Aircraft maintenance checks are *lighter* when the aircraft is in service (*e.g.* A and B checks, which are conducted without disassembly) and *heavier* when the aircraft is temporarily out of service (*e.g.* C checks with disassembly). The maintenance schedule depends on the fight cycles and flight hours [36].

In metal structures, impact damage is generally not a major safety concern (although metal fatigue can be a threat) because of the inherent material ductility and energy absorbing mechanisms. In contrast, composite structures are inherently brittle (the fibres are brittle, and so is the matrix when compared with ductile metals) and can only absorb energy in elastic deformation and through damage mechanisms—making them sensitive to impact damage [39]. Moreover, the impacts on composite structures are generally in the transverse direction (*i.e.* normal to the plane of the fibres), which in the absence of through-the-thickness reinforcement has relatively low damage resistance. In high-velocity impact, the material response is dominated by stress wave propagation and does not have enough time to trigger quasi-static damage mechanisms—leading to localized damage [40]. In low-velocity impact, as the contact duration is long enough for the entire structure to respond to the impact load, the dynamic structural response of the component is of importance and as a consequence more energy is absorbed elastically [40].

A considerable reduction in compressive, tensile and shear strength is often caused by impact damage [41,42], depending on the impact energy and impactor diameter. Blunt impacts can induce sub-surface damage without visible surface damage [43]; it is thus difficult to identify such damage during visual inspections [44]. Impact loads can cause delamination, dents and punctures as well as micro-damage (*i.e.* matrix-cracking, fibre-breakage). Delamination damage occurs at the interface between the laminae of a laminate or between skins and the core of sandwich panels. Delamination can considerably reduce the structural stiffness and strength of composite components. With low velocity impacts, dents are typically an indication of sub-surface damage [43], which can consist of laminate delamination, debonding of skin and core, matrix cracks and fibre breakage. However, with a higher impact energy and smaller impactor, a puncture is more likely to occur than a dent. A puncture may have delamination, matrix damage, and fibre breakage around it. It is important to note that fibre-breakage, unlike matrix-cracking, can be critical as key material properties are dominated by fibre reinforcement. Such fibre failure is usually localized to the impact zone, depending on the impactor size and impact energy [40].

In general, damage to composite components needs to be assessed by using suitable non-destructive techniques to determine the extent and location of the damage as a first step to decide whether to repair or replace the damaged component. If damage is not widespread and extensive, structural repair is the only feasible solution as replacing the entire component is not cost-effective in many cases [45]. Non-destructive inspection methods used in a manufacturing environment are often more stringent than the methods that can be practically suitable for on-aircraft inspection [35]. For example, inspection with access to only one side of the composite component is often a major constraint, especially for in-service checks. Non-contact non-destructive techniques that can scan large areas with high speed and detect sub-surface damage are ideal for aircraft composite structures [34]. Moreover, as the reduction in material strength depends on the type and size of damage, accurate damage detection and quantification are essential for a robust aircraft structural maintenance and repair strategy.

3.2. Structural repair

The primary objective of any structural composite repair technique is to restore the strength and stiffness of a damaged component and bring its original service condition (*i.e.* structural and operational efficiency) back as much as possible [45]. Depending on the type and location of the damage, structural composite repair can be injection, doubler or scarf based [46]. While resin injection repair is generally regarded as a temporary measure to stop the spreading of damage, doubler repair can provide a permanent restoration of structural strength, but not an aerodynamically smooth surface. Scarf repair can offer structural strength as well as a flush surface, and thus have greater potential for aircraft composite repair, especially for external skin panels. In designing a composite repair, other factors such as durability and operating conditions must also be considered to ensure the effectiveness and structural integrity of the repair. Composite repairs are either mechanically fastened or adhesively bonded patches. Mechanically fastened composite repairs are not generally acceptable on thin laminates or sandwich structures because of the stress concentrations induced by mechanical fasteners [47,48]. Bonded composite scarf repairs are generally preferred as they can provide better joint efficiencies and a superior aerodynamic surface [45,49]. In Fig. 1, subsurface damage typically induced by low velocity blunt impactor and subsequent bonded repair with scarf and stepped scarf patches is schematically shown. As the adhesion of carbon-fibre and resin system is fundamental to manufacturing composites, a bonded scarf patch is a natural choice to achieve effective stress transfer mechanisms.

In a bonded repair, adhesive bonding of the parent and repair materials is an important factor. The bond strength, which depends mainly on surface treatment, adhesive type, curing conditions and joint design, must be sufficiently high to ensure that stresses are safely transferred between the two adherends [50]. The design of bonded repairs should aim to provide a shear dominant stress state and induce minimum peel (*i.e.* through-thickness normal) stresses in the adhesive layer to improve the joint strength [51]. In general, bonded scarf patches, with no eccentricity of the load and minimal peel stresses, are the most efficient joints for bonded repair. On the other hand, scarf repairs require the removal of large amounts of undamaged material to provide a shallow scarf angle, which may cause further damage to the parent laminate. In addition, *in situ* scarf repair poses several challenges [52] such as accurate damage assessment, precise scarfing (*i.e.* obtaining the designed scarf angle), bondable (clean and active) scarf surfaces, controlled cure temperature and pressure *etc.*

3.3. Aircraft MRO

The MRO (maintenance, repair and overhaul) market is a key player within the aviation industry, given the importance of

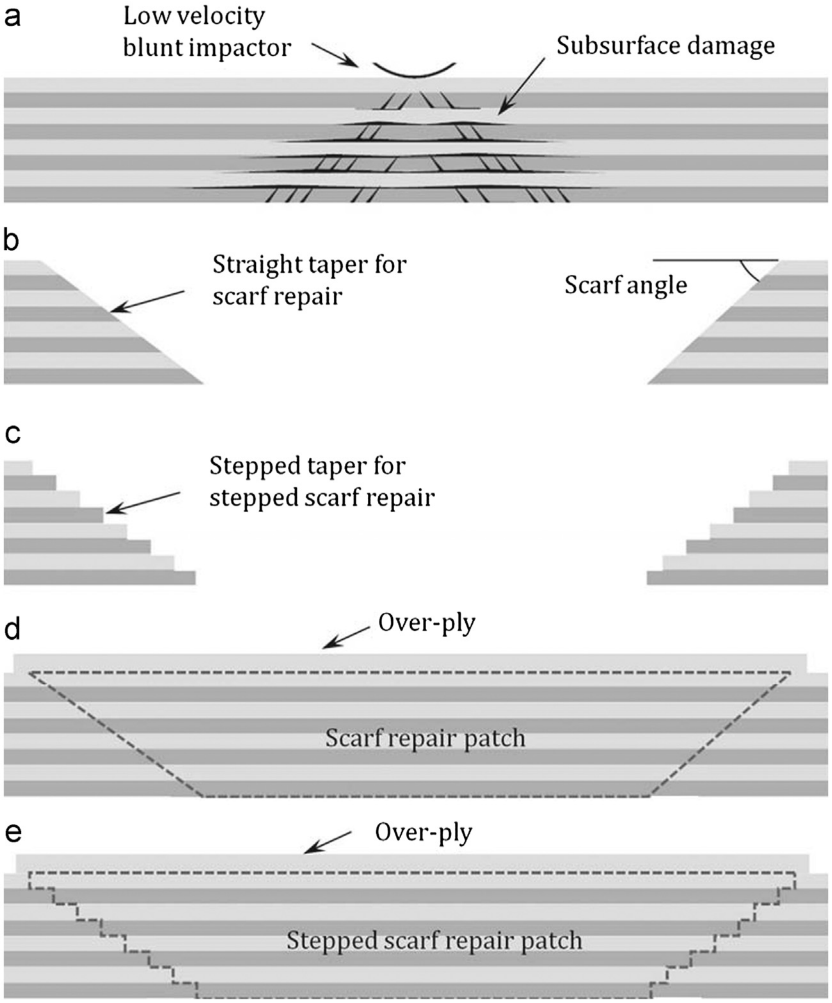

Fig. 1. Bonded composite repair: (a) subsurface damage typically induced by low velocity blunt impactor, ((b)–(c)) composite machining to achieve straight and stepped taper for scarf and stepped scarf repair, ((d)–(e)) scarf and stepped scarf repair patches with over-ply.

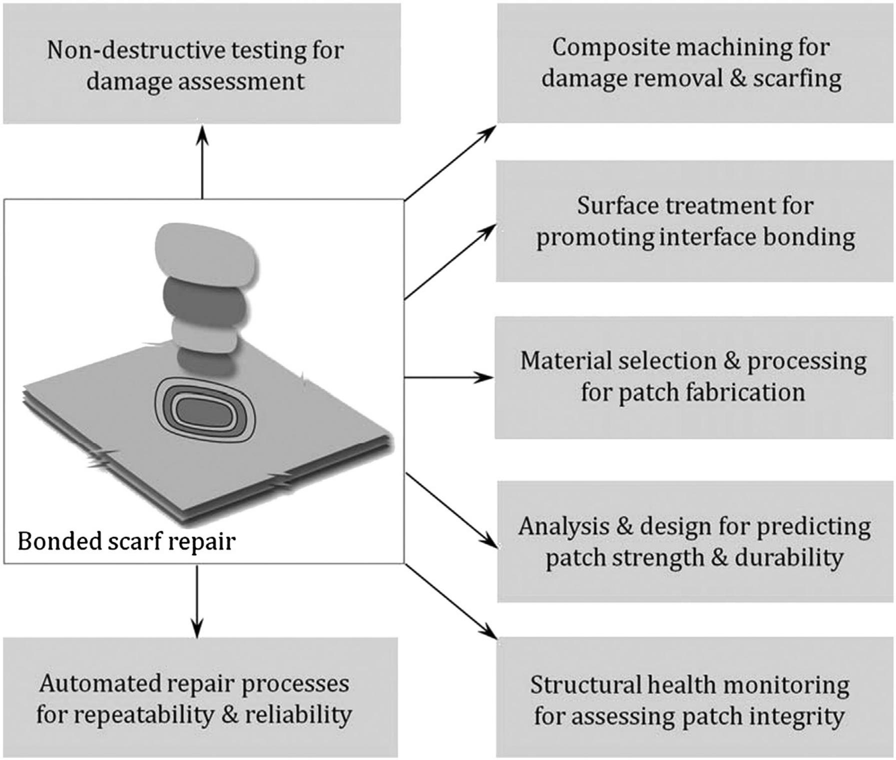

Fig. 2. Research challenges for developing robust bonded composite repair technology.

aircraft safety. According to a recent report from Lucintel [53] on growth opportunities for composites in the aerospace MRO market for the period 2011–2016, the global aerospace MRO market is expected to grow at a CAGR (compound annual growth rate) of 3.2%, and the aerospace composite components MRO market at a CAGR of 10.6%. Opportunities for composites repair in aerospace MRO can be expected in three segments namely primary aero-structures, secondary aero-structures and engine components.

4. Bonded repair: Research areas

Structural adhesive bonding as a joining technology provides many advantages in aerospace applications. Secondary bonding, with high performance structural adhesives, is often used in the assembly of composite structures [54]. For bonded structural composite repair, single or double-sided doubler patches [55–57], scarf or stepped scarf patches can be bonded to the damaged structure [49–51,58]. However, accessibility to both sides of the damaged region is often restricted, especially when the damaged component is not disassembled. Bonded doubler repairs are relatively easy to perform as no material is removed from the parent structure, but they are only suitable for thin cross-sections and do not provide smooth surfaces [46]. Scarf patches are in general suitable for permanent repair of thick cross-sections [52]; however the repair needs accurate processing techniques and trained technicians to precisely implement standard procedures (*e.g.* structural repair manuals) [52]. Scarf repairs can be conducted with access to one side of the damaged component; they can also provide effective stress transfer and a good aerodynamic surface finish.

The saying *the devil is in the detail* is certainly relevant to composite bonded repairs, especially to primary structural components. For structural bonded scarf repair of composites by using conventional (manual) repair procedures, suitable techniques for damage assessment, material removal, surface preparation, patch fabrication, and controlled curing (temperature and pressure) are essential [45]. Each one of these aspects poses different challenges in order to make reliable and consistent repairs without human error [59]. However, as the demand for more reliable and repeatable repair procedures for both primary and secondary composite structural members has been increasing, research activities on bonded composite repair have globally gained momentum in the composite industry as well as in academia. The research activities are focusing on several key areas, ranging from damage detection techniques to automated repair technologies.

In this paper, the key elements of structural bonded scarf repair, as shown in Fig. 2, are reviewed. The scientific aspects are broadly divided into six categories: (a) damage assessment, (b) material removal, (c) surface preparation, (d) patch fabrication, (e) design, and (g) monitoring and automation. The areas of damage assessment (*i.e.* potential NDT techniques), material removal (*i.e.* composite machining), surface preparation and patch fabrication, which are essential for implementing bonded composite repairs, are covered in Sections 5–8. The aspects of patch analysis and design, strength and durability, which are important to ensure structural integrity, are covered in Section 9. The topic of monitoring repair patches and future opportunities for bonded repair automation are reviewed and discussed in Section 10.

5. Damage assessment: Non-destructive testing

Structural damage needs to be accurately assessed to perform an adequate bonded repair. As impact damage is critical to composite material performance [39], structural damage needs to be accurately located and quantified. Locating damage is not always straightforward as barely visible impact damage (BVID) is common in composite laminates [43]. Subsurface damage in composite materials can be in the form of matrix-cracking, fibre-matrix debonding, fibre-brakeage and delamination—ranging in size from couple of microns to several centimetres. Moreover, as the damage mechanisms in composites are often very complex because of their inherent non-homogenous and anisotropic material behaviour, non-destructive inspection poses several challenges for accurate and reliable damage assessment [60–63]. Several non-destructive testing techniques are employed for different damage types, but there is no unique technique available that can accurately evaluate all damage types in composite materials [34].

Visual inspection, which is quick and low cost, is the most obvious approach to assess surface damage, especially for visible cracks, dents and punctures. Factors such as surface cleanliness, colour, finish, illumination, environmental conditions and even the inspector's vision can influence the outcome of the inspection [64]. If any surface defect is detected, a more sophisticated non-destructive technique can later be employed. Similarly, a tap test is also an inexpensive inspection technique [65], which has in recent years been automated (*e.g.* Woodpecker [66]) for greater accuracy. Areas of good bond will sound clear and of a higher frequency than disbonded or delaminated areas, which give a dull sound of lower frequency. Although the tap test is low cost and quick, it cannot locate smaller defects and is also ineffective for thick composite sections. In this regard, more advanced non-destructive techniques, such as ultrasound, thermography and shearography, have potential for accurate and reliable damage detection.

5.1. *Ultrasonic techniques*

Ultrasonic testing is an established non-destructive technique for detecting subsurface damage in composites [60]. When ultrasonic waves travel through composite materials, the wave propagation is influenced by internal damage (*e.g.* delamination or disbonding), which act as discontinuities and introduce a local change in acoustic impedance. In direct ultrasonic techniques, high frequency waves are generated by a transducer and transmitted to a test component; then the reflected or transmitted waves are received by the same or a second transducer [67]. High frequency waves are more sensitive to defects; whereas, low frequency waves can penetrate to greater depths [68]. With contact transducers, a thin layer of couplant (*e.g.* oil) is used between the test surface and the transducer to transmit waves without large attenuation. With immersion transducers, which are not in contact with the test surface, the test component is immersed in couplant (often water) to facilitate wave transmission. A waterjet coupled transducer can also be used to transmit waves and scan composite laminates. From a composite repair viewpoint, conventional ultrasonic techniques offer several advantages. Ultrasonic testing can detect different defects (*e.g.* delamination, voids or disbonding) and indicate the depth of a defect in a laminate. Scanning systems can be portable to inspect large areas. Scans with pulse-echo mode can be used with access to only one-side of the test surface. However, one major disadvantage of direct ultrasonic techniques is the need for a liquid couplant to overcome the acoustic impedance mismatch between air and composite materials [69]. Without a couplant, the majority of the sound energy is lost and very little is transmitted into the test component. A couplant displaces the air between the transducer and the test surface and minimizes the energy loss. Scanning with a couplant can be complex and often not practical for *in situ* inspection of large composite structures [70].

In contrast to direct techniques, indirect ultrasonic techniques such as laser-based ultrasound do not require conventional transducers to generate ultrasonic waves at the test surface for transmission and conversely on reception [71,72]. A short pulse laser is used to generate waves; a long pulse or a continuous wave laser is used as an *indirect* approach to detect the waves. When a laser pulse strikes a composite material, it rapidly expands the material locally and creates a thermo-elastic ultrasonic pulse [73]. Moreover, with higher pulse energies above the ablation threshold of the material, the laser pulse vaporizes the test surface forming high temperature plasma and creating an ultrasonic wave (in addition to those generated thermo-elastically) [72]. Interferometry (*e.g.* Fabry–Perot) can be used to detect ultrasound waves [74]. The main advantages of laser ultrasound technique are: non-contact inspection, couplant-free scanning, inspection with access to only one-side of the test component, and inspection of complex shapes from greater distances. On the other hand, a laser-based ultrasonic inspection system, which requires two laser systems and interferometer, is expensive in comparison to the conventional transducer-based systems [71]. Moreover, as material induced wave phenomena is used to optically detect damage, sensitivity of laser ultrasound techniques could be an issue.

5.2. *Thermography*

Thermography is a non-contact technique based on infrared radiation for detecting material damage or defects [75]. In thermography, which can be either passive or active, temperature gradients are measured to detect material damage non-destructively [76]. While passive thermography is used for components that are at a different temperature than its surroundings, active thermography involves heating the component surface rapidly by using an external heat source and observing how the temperature decays with time [77,78]. As composite materials possess a relatively low thermal conductivity, thermographic techniques are well suited for the inspection of composite structures [60]. Infrared cameras are used to capture thermal images; advanced software is then used to process these images for detecting subsurface defects. In relation to repair, subsurface damage in composites (*i.e.* delamination, disbonds, cracks, or moisture) affects local thermal conductivity and manifests in local temperature gradients within the damaged region [75]. The detected subsurface damage can be quantified in terms of depth and size. Thermography enables large area inspection to be conducted to detect subsurface damage. Once damage is identified, another technique such as ultrasonic testing can be used for a detailed local inspection [79]. Thermography can also be used to inspect bonded repair patches [80]. The major advantages of thermography are non-contact non-destructive inspection with access to only one-side, inspection of large and complex surfaces in quick time, and data processing in pictorial format for rapid decisions. However, active thermography is relatively expensive with current technology as high sensitive thermal cameras and external heat sources are required. The technique could be less sensitive to subsurface defects in thicker laminates.

5.3. *Shearography*

Shearography, which is an interferometric technique, uses coherent laser illumination for surface deformation measurements (*i.e.* displacements and displacement derivatives) non-destructively [75]. Compared to holography, which measures surface displacements, shearography measures derivatives of surface displacements and thus provides surface strains [81,82]. The technique has significantly been improved in recent years with advancements in charge-coupled device (CCD) cameras, lasers and computing hardware. Digital shearography is a non-destructive testing suitable for composites due to its ability to provide non-contact, full-field measurements. The technique uses the coherent, monochromatic properties of laser light to generate speckle patterns on the test surface. The speckle patterns on the test surface are recorded—one image when the specimen is unstressed and one with an applied stress. The technique requires an image shearing device (*e.g.* Michelson interferometer) in front of the CCD camera [83]. When the test component is subject to an applied load, subsurface damage will exhibit strain anomalies compared with the regions that are free from damage. Digital shearography can be used to detect the damage-induced surface strain anomalies. Shearography is particularly effective in revealing impact damage in composite structures [84]. Common loading techniques include thermal loading (*e.g.* high power flash lamps), pressure loading (*e.g.* vacuum) or vibrational excitation. The inspection results are shown in real time to the user and systems can be configured to automatically detect/measure defects in composite structures—including delamination, disbonds, kissing bonds, impact damage, wrinkles, and dry spots [81]. Shearography increases inspection speed of large composite structures [34,70] and also enables non-destructive testing of adhesively bonded repair patches [85]. However, as shearography directly measures surface strain anomalies in the component, the success in detecting damage/defects depends on their size and location [76,81,82,86].

6. Material removal: Composite machining

When damage is non-destructively identified and assessed, the damaged region needs to be accurately machined to remove material and taper edges for implementing bonded scarf repairs. But composite machining poses several problems (*e.g.* edge damage, delamination, matrix-cracking, fibre pullout) because of the inherent material anisotropy and non-homogeneity [87–89]. The machinability of composites depends on physical and mechanical properties, which themselves depend largely on the type of fibre, fibre content, fibre orientation and matrix material [90]. The machining/scarfing (*i.e.* damage and material removal) of composites is thus a key process parameter in bonded scarf repairs. Moreover, the scarfing of curved composite surfaces is more complex than flat surfaces and thus requires accurate machining to achieve a designed scarf angle. In a conventional approach, the damaged material is removed and the edges tapered by mechanical machining processes (*e.g.* cutting, grinding, sanding) to achieve a designed scarf angle for either a straight or stepped bondline. Manual processes (*i.e.* using hand-held machining tools) can lead to inaccurate scarf geometries; thus the accuracy and quality of the machined region largely depend on the skills of repair technicians [91]. Non-traditional machining approaches, such as pulse-laser and abrasive-waterjet based techniques, could provide opportunities to improve and automate the process of damaged material removal for bonded repairs.

6.1. *Conventional machining*

The machining of composite materials, having distinct fibre and matrix phases, is more complicated than that of metals/alloys [88]. Conventional machining of composites is difficult because of their heterogeneity, anisotropy, low thermal conductivity, heat sensitivity and high abrasiveness [88–90]. The fibres are strong and brittle; the polymer matrix is in comparison weak and ductile. The machining of composites by conventional processes is characterized by intermittent micro-fracture because of the contrasting response of the fibres and polymer matrix to the applied mechanical forces [92]. The machined surface quality is thus largely depends on the type of fibre as well as the fibre orientations. Fibres conduct heat along their direction and thus dissipate heat away from the machining zone. But the polymer matrix, with its poor thermal properties, cannot endure high temperatures that are often induced during machining and thus requires a coolant for heat dissipation. On the other hand, moisture absorption by the polymer matrix with the application of a liquid coolant may adversely affect dimensional accuracy, surface properties, and mechanical properties of the machined region [93].

The machining quality manifests in geometric features (*e.g.* surface quality) and the extent of material damage (*e.g.* edge delamination) caused by the process parameters. High machining forces will be generated when inappropriate machining conditions (*e.g.* speeds, feed rates, tool geometries, tool wear *etc.*) are used, and consequently cause material damage during machining (*e.g.* delamination) [93]. Moreover, as residual stresses are often introduced (intra-lamina and inter-lamina) after curing because of the difference in thermal expansion coefficients of polymer matrix and fibres, the internal stresses will be released during machining and may sometimes deform and damage the component. The debris can also be a health hazard in the absence of proper dust extraction systems during manual machining [88]. Complex systems, however, are required to automate mechanical-based scarfing of laminates for bonded composite repair [94,95].

6.2. *Laser machining*

Laser machining of composites provides several advantages in comparison to conventional machining processes [88,96]. Laser machining offers the accurate damage removal and scarfing of composites and thus provides opportunities for bonded composite repairs [97,98]. But it is worth noting that laser machining of composites is a complex process because the fibre and polymer matrix phases, which have considerably different physical and thermal properties, respond differently to high energy lasers [99]. In comparison to the fibres, the polymer matrix materials have a high absorption coefficient, low thermal conductivity, low thermal diffusivity, and low ablation threshold [88]. Epoxy matrix materials are removed by complex laser-material interaction and degradation mechanisms (*e.g.* ablation) above their ablation thresholds [97]. The fibres require higher temperatures and longer exposure time to machine. Carbon fibres, with higher thermal conductivity, dissipate heat into the bulk of the material and can cause a large heat-affected-zone (HAZ) if appropriate laser process parameters are not used [100]. In contrast to continuous lasers, pulsed lasers can provide significant improvements in machining quality. Short pulsed lasers offer better process parameters (*e.g.* shorter laser-material interaction time, higher energy, better focusing) and consequently help achieve a smaller HAZ than a continuous laser [100,101].

As laser machining is fundamentally a thermal process, external mechanical forces, which can cause distortion and material damage, are not required during machining [88]. Furthermore, as the machinability is not affected by the material strength and hardness, laser machining can be advantageous for heterogeneous materials such as composites. It also offers flexibility to machine components with complex shapes as it is a non-contact machining process. However, one of the major issues with laser machining of composites is the formation of HAZs which can adversely affect the material properties [100]. To minimize the HAZ, optimized laser process parameters, which depend on the type of fibre and matrix material, need to be identified and used [101,102]. The other major issue is the toxic by-products [103], which could pose a health risk to repair technicians, generated from the laser-composite material interactions during machining. For bonded composite repairs, a computer controlled laser machining system is required to machine designed scarf angles and shapes.

6.3. *Abrasive waterjet machining*

In abrasive waterjet (AWJ) machining, a waterjet is used together with abrasive particles at extremely high speeds for machining of composites through an accelerated micro-erosion process. Water is pumped at high pressures through a nozzle to form a coherent stream flowing at high speeds [104]. As the motion of the nozzle is controlled, geometric accuracy is achieved. But the machining quality depends on several factors (*e.g.* water pressure and flow rate, mixing tube diameter and length, abrasive particle size and shape, abrasive material, abrasive flow rate, traverse speed, stand-off distance, inclination angle *etc.*) [88]. AWJ machining involves complex interactions between the abrasive particles, the flow development and the target material [105]. As abrasive particles impact the material surface at high velocities, material removal at micro-scale occurs by particle impact erosion mechanisms, which depend on the target material and abrasive particle properties [106–108]. The erosion mechanisms for brittle materials are governed by indentation fracture through microcrack formation, propagation, and interaction. The macroscopic interaction of the abrasive waterjet with the target material is responsible for kerf formation, material removal and machining [88].

AWJ machining can be used to accurately remove damage from composite components and thus offer opportunities to achieve complex scarf geometries for bonded composite repair [109]. With appropriate process parameters and controlled motion of the nozzle over the component predetermined shapes (*i.e.* straight or stepped scarf geometries) can be machined. As water is involved in the machining process, AWJ techniques eliminate the issue of heat-affected-zones and tool wear. The machining process eliminates toxic fume and also wash away hazardous debris from the machined region; it is thus an environment-friendly process [88]. On the other hand, AWJ machining, depending on process parameters, may introduce delamination and promote water penetration [110]. As water is used in the machining process, adhesive bonding of wet composite surfaces can be an issue for bonded repairs. For on-aircraft bonded repair, a waterjet system that can accurately remove material (without damaging any other components near the repair region) and effectively collects the used water and abrasive slurry is required. However, such AWJ systems would require complex setup and could also be expensive.

7. Surface preparation: Interface phenomena

Adhesion is one of the key factors that govern the mechanical properties of composite materials. The adhesion between the fibre and matrix phases is fundamental to the intra-lamina mechanical properties, while the inter-lamina adhesion is fundamental to the laminate properties. Adhesion is an inter-atomic and intermolecular interaction phenomenon at the interface of bonding surfaces [111]. As surface properties (*i.e.* conducive physical and chemical conditions) are important for promoting strong interface bonds, the aspect of surface preparation is thus critically important in both secondary bonding and bonded composite repairs [112,113]. Composite materials usually require surface preparation to enhance interface adhesion prior to secondary bonding. While secondary bonding of composites in a manufacturing process can be performed in controlled conditions, the repair processes (*e.g.* damage removal) and conditions (*e.g.* humidity or chemicals) often contaminate composite surfaces prior to bonding. The cleaning and preparation of composite surfaces prior to bonding is thus critical to ensure strong interface adhesion in structural bonded repairs.

The fundamental mechanisms that govern adhesion are not yet fully understood, although considerable research has globally been carried out for several decades [114]. Different adhesion theories have been proposed based on scientific concepts such as mechanical interlocking, molecular bonding and thermodynamics; but currently there is no unified adhesion theory that explains all the adhesion mechanisms [115]. The topic of adhesion is multidisciplinary in nature and involves several elements of polymer science, surface engineering, mechanics of materials and other related topics [114,115]. Factors such as low surface energy, chemical inertness, surface contamination and a weak boundary layer often contribute to poor wettability and weak interface adhesion in polymer composites. A misconception about surface preparation prior to bonding is that a clean surface (*e.g.* free from dust, lubricants or other surface contaminants) is the only requirement for better adhesion. A clean surface is only a necessary condition for adhesion, but not sufficient to achieve strong interface bonds [54]. Good adhesion requires very close contact; adhesive needs to flow and wet the surfaces to be bonded [116]. To ensure good surface wetting, the surface energy of the adherend must be higher than that of the adhesive used for bonding [117]. Surface preparation is thus essential to modify the physical and chemical properties of the surfaces, increase surface energy and remove contaminants and weak boundary layers [118,119]. Appropriate surface preparation will promote adherend–adhesive interface bond strength and improve structural performance (*i.e.* strength and durability) of adhesively bonded joints. Surfaces that are either untreated or insufficiently prepared prior to bonding could lead to adherend–adhesive interface fracture reducing the joint efficiency.

With regard to bonded composite repair, the machining process used will remove material damage and create new surfaces (*e.g.* tapered scarf surfaces). The surfaces often require mechanical abrasion to achieve surface uniformity and solvent cleaning to remove debris, dust or any surface contaminants [45]. But the type of surface preparation can depend on the machining process used in creating the surfaces. In general, a variety of surface preparation (*e.g.* abrasion/solvent cleaning, grit blasting, low-pressure plasma treatment) can be used to enhance surface energy, increase surface roughness, activate surface chemistry, and thereby increase bond strength and durability of adhesively bonded composite joints [112]. Abrasion/solvent cleaning is the most commonly used technique for composite adherends to increase the mechanical interlocking of the adhesive into the adherend by removing contaminants and improving surface roughness. However, providing intimate contact between the adherend and adhesive is essential for intrinsic adhesion, which will lead to interatomic and intermolecular bonding and a stronger adherend–adhesive interface. Abrasive processes do not guarantee high surface wettability and surface energy that are required to provide intimate contact between the adherend and adhesive. Solvent cleaning could remove dust and debris; but solvent residue could adversely affect the adherend–adhesive interface properties. Moreover, a manual process could lead to nonuniform and inconsistent surface properties, and may also contaminate the surface. In this context, advanced surface treatments based on atmospheric plasma and pulsed laser ablation could offer opportunities for composite bonded repairs.

7.1. *Plasma treatment*

Polymer surfaces can be modified by exposure to a low pressure or atmospheric plasma. As plasma consists of charged particles (*i.e.* electrons, ions and radicals), a plasma surface treatment can provide chemical modifications to polymer composites, and thus enhance surface free energy and wettability for adhesion [120–122]. Polymer surfaces are exposed to a cloud of plasma either inside a vacuum chamber (*i.e.* low pressure plasma) or at ambient pressure (*i.e.* atmospheric plasma) by ionizing a gas with an energy source. The complex plasma-material interactions lead to surface reactions and consequently modify surface properties [123]. A few molecular layers will be modified when polymer composites are in contact with plasma. The reactive species in the plasma interact with the surface molecules and produce functional groups. It is known that low pressure plasma treatment can significantly improve interface adhesion in composite bonded joints [124–127]. But low pressure plasma treatment requires a complicated setup to achieve low pressures, which can be difficult or even impossible to achieve, on large composite surfaces. On the other hand, an atmospheric plasma treatment does not require low pressure conditions and can be generated at the tip of a nozzle [128]. Atmospheric plasma treatments provide opportunities for surface preparation of complex and large composite surfaces. In comparison to manual abrasive processes, atmospheric plasma treatment is a non-contact process that can yield surface uniformity and process repeatability. The process could be automated as the plasma is delivered onto the surface in the form of a jet. Plasma-material interactions, however, are complex and depend on the material properties as well as the plasma source and parameters. The modified surface properties could be lost over time (*i.e.* hydrophobic recovery) when the surfaces are exposed to ambient conditions [129]. Plasma treatment of composites requires expensive systems in comparison to the conventional surface treatments. With regard to composite repair, the debris and dust generated during damage removal need to be removed prior to plasma treatment (plasma-material interaction is limited to a very thin surface layer).

7.2. Laser treatment

The interaction of a laser with polymer composites can modify the physical and chemical properties of the surface through photo-thermal and photo-chemical processes—depending on the laser parameters and material properties [123,130]. High temperatures generated by pulse lasers can break chemical bonds and thus form functional groups, which chemically activate the surface for adhesive bonding [131–134]. Pulse laser ablation of the matrix phase will occur above the ablation threshold, and hence remove material and improve surface roughness [135]. Laser-based surface preparation for adhesive bonding of composites can provide advantages. As lasers can be employed to accurately deliver a large amount of energy onto a localised region of composite surfaces, the surface properties can be accurately engineered without altering the subsurface material. In comparison to abrasive processes, laser surface treatment is a non-contact and controlled process, and provides opportunities for uniformity, repeatability and automation. However, laser-material interactions are complex and depend on the material properties (*e.g.* optical and thermal properties) as well as the laser parameters (*e.g.* wavelength, power, mode of operation, interaction time) used [88]. The optical and thermal characteristics, which substantially influence the surface condition during and after laser processing, of the material should be known prior to laser treatment. The rate of material or contaminant removal with laser ablation depends on parameters such as frequency, pulse duration, pulse repetition rate, laser energy density. As polymer materials absorb different amounts of energy at different wavelengths, laser wavelength is an important parameter for surface modification of composites. The type of laser (*e.g.* Nd-YAG, CO_2, excimer laser) used is the key in achieving the desired surface modification without affecting the bulk material properties. In comparison to conventional surface preparation (*e.g.* abrasion/solvent wiping), the laser processing of composites require expensive systems. But an integrated laser system, which is capable of damage removal and surface preparation, could provide opportunities for bonded composite repair [52].

8. Repair fabrication: Materials processing

The performance of composites and their bonded assemblies largely depend on the material systems used and the processes and conditions employed in manufacturing them. The structural behaviour of composite bonded repairs is no different. Suitable material systems (*i.e.* patch materials, resins, adhesives) and controlled curing conditions (*i.e.* temperature and pressure) are essential to fabricate a strong and reliable repair patch [136,58]. Moreover, the time required, which is directly related to the aircraft downtime, to fabricate and consolidate a repair patch will have a significant impact on the associated economical and operational aspects [35]. The material systems that can be stored at ambient temperature and cured at low temperature and short cycle time are thus ideal for repair applications [137–140], especially for *in situ* fabrication. In addition, it is often required to perform repairs with out-of-autoclave processes as using an autoclave is only feasible for components that can be removed, disassembled and placed into an autoclave [141]. Therefore suitable fabrication techniques that can provide the required cure conditions – to achieve adequate curing and consolidation of adhesive bondlines and co-cured patches, and acceptable material properties without internal defects – are required.

8.1. Hard and soft patches

After the damaged region is removed (Section 6) and a suitable surface treatment employed (Section 7), the scarf cavity can be repaired with a patch which is either pre-cured (*i.e.* hard patch) or fabricated *in situ* with pre-preg or wet layup (*i.e.* soft patch) [58]. In a pre-cured approach, a patch is manufactured by either using a mould that matches the scarf cavity or by machining the scarf contour required. The pre-cured patch can be bonded to the parent component by using an appropriate film adhesive relatively at a low temperature (*i.e.* only curing the adhesive film). As the pre-cured patches are not manufactured *in situ*, the properties of the patch (*i.e.* fibre-volume fraction and porosity) could match those of the parent component when the materials and process used to manufacture the patch matches those of the parent component. The pre-cured approach, however, is expensive, time consuming and requires additional process steps (*i.e.* machining of a contour mould or contoured patch) [58]. With a moulded patch, the pre-cured patch may not precisely fit into the scarf cavity if any local distortions occurred because of unbalanced laminae [142–144]. On the other hand, for a machined patch, contoured composite machining requires non-conventional techniques and may introduce distortion or damage. Pre-cured patches (either moulded or machined) require surface preparation prior to adhesive bonding. In this regard, a soft patch approach can be relatively less expensive, provide flexibility to patch complex scarf cavities, and would allow *in situ* patch fabrication.

In a soft pre-preg patch approach, pre-preg laminae are cut to match the scarf cavity and used in conjunction with a film adhesive to fabricate a patch and repair the component through the application of heat and pressure. As the fibre-orientation and layup influence the mechanical properties of the patch, each lamina needs to be accurately cut and located while fabricating the patch. Furthermore, pre-preg materials and film adhesives usually need to be stored at very low temperatures in freezers to prevent undesirable curing at ambient conditions. Dry fibre fabric can also be used to fabricate a soft patch with an *in situ* resin infusion process. The resin will also act as an adhesive to bond the patch to the parent component. The soft patch approaches require *in situ* curing of the patch and thus need elevated temperatures and pressure to achieve desired patch consolidation [141]. But, as the curing process would often have to use a vacuum bag together with a heat blanket, which can result in low fibre-volume fraction and porosity in the patch and also voids in the bondlines, it is difficult to achieve patch properties that match those of the parent component. For on-aircraft bonded repairs, the location of damage/repair could affect the manoeuvrability (*e.g.* top or bottom skin repair) required to fabricate a soft patch. Wrinkling of the co-cured patch can also be an issue with a soft patch approach [58]. In addition, moisture absorbed by the materials (*e.g.* pre-preg or film adhesive) prior to curing can also introduce porosity in the patch and bondlines [145,146]. But resin systems with low viscosity, low cure temperature and short cure time could provide opportunities to fabricate cost-effective scarf repairs. However, the material selection process for fabricating a patch will depend on the material systems used in the parent component to achieve a fully compatible repair patch.

8.2. Cure temperature and pressure

The manufacturing process of high-performance composites involves temperature, pressure and vacuum conditions to enable the curing reaction to take place and ensure good compaction of the laminate plies. Thermosetting resins such as epoxies, which are extensively used as matrix materials in composite laminates and as adhesives for bonding composites, polymerize at room or elevated temperatures, causing chemical changes in the molecular structure (*i.e.* cross-linking) [147]. The cure reactions are exothermic and strongly depend on the cure temperature and time [148]. Historically, the processing parameters of a cure cycle for composite laminates have been developed using trial-and-error methods [149]. The problem is partly due to the low thermal conductivity of most composite materials, which leads to thermal gradients, variations in degree of cure and residual stresses [150–152]. Considerable residual curing stresses could also be generated from the mismatch between the coefficients of thermal expansion of the fibres and matrix, and between adjacent laminae. The residual stresses can cause shrinkage and warpage of the component. In addition, factors such as entrapped air, absorbed moisture, gases formed during cure and geometrically constrained boundary conditions (*i.e.* fixed mould cavities) could lead to void formation [145,146,153–155]. Appropriate cure pressure is thus required to improve consolidation and reduce porosity.

In relation to bonded repairs, cure temperature is a key parameter that can have a direct influence on the quality of a bonded patch. Controlled heating is required to cure adhesives and co-cure composite patches. In case of humid conditions, it is necessary to dry surfaces and moisture in sandwich core prior to repair at elevated temperatures without over heating the parent component. Composite bonded repairs, especially when performed *in situ*, can be difficult to process as elevated temperatures are often required for curing the structural adhesives and composite resins used in the repair patch. For example, a single-sided heat source is often used to transfer heat through the full thickness of the repair patch to achieve uniform cure of the adhesive and co-cured patch. But composite laminates typically exhibit poor thermal conductivity in the through thickness direction, which may lead to a thermal gradient when a single-side heat source is used during repair [156]. The issue of thermal gradient can be significant if a sub-structure beneath the repair patch acts as a heat sink [35]. A thermal gradient could lead to non-uniform cure of the adhesive and co-cured patch; and consequently introduce non-uniform stress transfer and make the bonded repair ineffective. Complex cure temperature gradients may also increase the potential for process-induced warpage, residual stresses and matrix micro-cracking, and micro-delamination of the repair patch [157–159]; additionally over-heating may locally degrade the parent component (*e.g.* skin-core debonding in sandwich structures). Although heat blankets are commonly used for *in situ* repair, non-conventional heating methods (*e.g.* induction-curable adhesives and resins) have been shown to offer new opportunities [160–165]. However, optimal cure of adhesives and resins requires controlled cure cycles [147–149], and thus could be an issue with non-conventional heat sources.

Cure pressure, which is also an important parameter for bonded repairs, must be adequate to ensure proper bondline thickness, minimise bondline porosity, and cause the adhesive to flow and properly wet the surfaces [166,167,168]. For co-cured composite patches, pressure is required to consolidate the composite in order to obtain the desired mechanical properties. Pressure can be applied by using a vacuum bag [169] or mechanical approach [170]. Vacuum bagging, which is the most common because of its convenience, can conform to any surface, apply uniform pressure, remove volatiles and hold a heat blanket in place. Vacuum pressure will help remove air entrapped during fabrication (*e.g.* air between the film adhesive and the machined scarf surface) and volatile gases during cure, thus reducing the material porosity [167]. However, it is not possible to achieve high pressure by using vacuum bagging alone. This could lead to inadequate consolidation of co-cured patches and consequently affect the fibre-volume fraction and mechanical properties. On the other hand, approaches to mechanically apply pressure need complicated fixtures and must be held against the structure by a support mechanism. Moreover, the curvature of the repair region could adversely affect the pressure distribution and thus may not be uniform for complex surfaces.

9. Design of repairs: Mechanics of bonded joints

To restore the as-manufactured mechanical properties (*i.e.* strength and stiffness) of the damaged parent component using a bonded repair, the structural response of bonded patches needs to be accurately analysed and designed by incorporating geometrical and material parameters. It is important to note that the structural behaviour of bonded repairs heavily relies on processing factors (*i.e.* surface properties, adhesion and curing conditions) rather than mechanics (*i.e.* stress and strain) alone [171]. By comparison, the performance of mechanically-fastened composite joints mainly depends on the mechanical factors such as bolt load and bolt-composite mechanical interactions [172,173]. This difference is a major challenge to provide strong, durable and reliable bonded scarf repairs, especially for primary structural components.

9.1. Analysis and design

The stiffness and strength of a bonded repair patch depend on the type of raw materials (*i.e.* soft or hard patch, adhesive), geometrical parameters (*e.g.* shape, scarf angle) and process parameters (*e.g.* surface treatment, cure conditions) that are used in the repair. The design of bonded repairs thus requires a comprehensive analysis of the stress transfer phenomena in the adhesive bondlines as well as in the two adherends under service loads. The design must also ensure that the bond between the two adherends transmits the service loads (*e.g.* tension, compression, fatigue) under environmental (*i.e.* humidity and temperature) service conditions [174–176]. The design should ideally ensure that the strength of the bonded repair is higher than the un-notched strength of the parent adherend so that failure occurs in the parent adherend before the bonded patch fails.

The extent of the material damage can be uncertain and depends on the source and nature of the damage. On the other hand, the amount of material that needs to be removed from the parent component for a scarf repair not only depends on the amount of damage, but also on the geometrical parameters (*e.g.* patch shape, scarf angle) of the patch designed. Some undamaged material around the damaged region needs to be machined in order to achieve the designed patch geometry. Whereas a circular scarf repair is appropriate for quasi-isotropic composite laminates, a constant scarf angle in every direction may be overly conservative for orthotropic laminates that make up the majority of aircraft external structures [49]. In addition, the amount of undamaged material removed could have an adverse affect on a component that is designed to take high stresses in only one direction [49]. To minimize the removal of undamaged material from the component, the design of scarf repairs needs to be optimized for a given repair condition. An optimised repair design minimizes the amount of material to be machined from the component and may consequently reduce the time required to complete the repair.

Structural repair with bonded scarf patches should ideally maximise the repair efficiency and minimise the risk of structural failure by effectively transferring different service loads (*e.g.* static, fatigue) through it. As the structural performance of bonded composite patches depends on manufacturing, material and geometrical parameters, predicting the behaviour of bonded patches by including all the associated parameters is thus very complicated. In comparison to the analysis of composite bonded joints with single joint configurations (*e.g.* single or double lap joints), the prediction of the structural response of a bonded scarf joint in a composite structure is relatively more complex because of the stiffness variation along the parent-patch interface. The stress distributions (*i.e.* peel and shear stresses) vary significantly along the parent-patch interface, depending on laminate thickness, material properties, and the stacking sequence [177]. In general, the composite laminate strength in the overlap section of the scarfed lap joint is usually reduced when compared with the parent laminate strength—due to discontinuous fibres over the overlap length as well as stress concentrations in the bondline and laminates. In addition, the bond strength could vary, which is a characteristic feature of adhesively bonded joints (especially with brittle adhesives), due to variations of the associated material, geometrical and processing properties [178–182]. The manufacturing processes could introduce different types of defects (*i.e.* bondline porosity, laminate porosity, kissing bonds) [126,183,184]. It is thus important to investigate the reliability of bonded patches subjected to different service loads/conditions and predict the failure behaviour.

For the analysis of adhesively bonded joints, approaches based on analytical (*i.e.* closed-form solutions) or numerical methods are commonly used. But the majority of the existing analytical models for adhesively bonded joints are two-dimensional, which assume a plane stress or strain state in the third direction, thus neglecting the stresses generated across the third direction (*i.e.* stress caused by the Poisson's effect) in the adherends [185–190]. Moreover, most of the analyses are linear-elastic for both adherends and adhesive as nonlinear material and geometrical behaviour is difficult to incorporate in analytical models. Accurate analysis of bonded scarf repairs by incorporating complex three-dimensional geometrical parameters is thus not feasible with closed-form analytical methods [191]. Computational models, on the other hand, provide a general tool for the analysis of arbitrary geometries and loading conditions. Numerical methods (*e.g.* finite element method) are commonly used to perform non-linear stress analyses and predict critical stress regions. Modelling approaches based on damage or fracture mechanics can be employed to investigate the influence of different design parameters on the joint strength and failure behaviour (*i.e.* damage initiation/propagation, locus of failure) [192–195]. But complex material models (and thus material data) are often required to accurately analyse the structural failure behaviour of bonded joints subject to service conditions (*e.g.* temperature and humidity) [196–200]. Furthermore, as the bondline thickness is much smaller than that of the adherends, the finite element mesh must accommodate the small dimension of the bondline as well as the larger dimension of the patch. As stress concentrations often exist in the bondlines, it is also essential that the bondline be modelled by a finite element mesh that is smaller than the bondline thickness [192]. This leads to a large number of degrees of freedom in the computational model, which requires efficient computational tools (*e.g.* explicit solvers) to reduce the analysis time. Numerical models based on a multi-scale approach may provide opportunities to handle the scale effects associated with bonded patches [201]. Furthermore, finite element models combined with statistical and probabilistic methods (*e.g.* Taguchi, response surface, Monte-Carlo techniques) could offer opportunities to analyse the variation in the joint strength and to identify critical process parameters [202,203]. Numerical models, when calibrated and validated experimentally, provide opportunities to design and optimise bonded repair patches. In relation to structural bonded repairs, a dedicated software tool [204] that can offer a quick and accurate analysis would play a significant role in the design of bonded repairs. Moreover, the details of the parent component as well as the mechanical properties of the repair materials (*e.g.* adhesive, laminate properties) need to be known and should be made available through structural repair manuals to facilitate the analysis and design of bonded composite repairs.

9.2. *Strength and durability*

Bonded joints may in theory be designed such that the adhesive can sustain loads greater than the strength of the parent material, ensuring that the adhesive will be able to sustain all possible load cases for the original structure [187–189]. However, many adhesive bonds fail in service because of inconsistent processing methods, while factors such as deficient design or poor materials selection could also play a role [175]. Variability in process conditions, which is highly relevant to bonded repairs (especially for *in situ* patch fabrication), can significantly contribute to the poor performance of bonded patches. While the mechanical properties of the parent laminate depend on the materials and processes used to manufacture the whole component, the mechanical properties of the patch laminate, parent-patch interface largely depend on the raw materials and process parameters employed during the fabrication of the repair patch. Process induced defects will degrade the mechanical properties of the patch laminate and bondline, and also generate stress concentrations in the patch when subject to external loads. As failure often initiates at stress concentrations, it is critical to use appropriate process conditions (*i.e.* uniform surface treatment, uniform cure temperature and consolidation) to reduce process induced defects. As the mechanical properties of brittle adhesives are often sensitive to porosity and stress concentrations, adhesives with low modulus and high ductility could minimize bondline stress concentrations and thus improve the joint strength and reduce its variation [205,206]. Toughened structural adhesives offer opportunities to enhance damage tolerance of bonded repairs [207,208].

Unlike bonded joints with metal adherends, the failure behaviour of bonded joints with composite adherends largely depends on the transverse tensile strength (*i.e.* through the thickness of the laminate) of the two adherends [209]. The transverse mechanical properties of composite laminates (with no through-the-thickness reinforcing fibres) are relatively lower in comparison to the in-plane mechanical properties of the laminate. As bonded joints induce peel stresses in addition to shear stresses along the bondline, the low transverse tensile strength, which is of the same order or even lower than that of the matrix, could lead to the adherend failure in transverse tension before the failure of the adhesive occur [54]. The peel stresses could damage (*e.g.* by delamination) the parent or patch laminates and thereby adversely affect the stress transfer capacity of the repair patch. It is thus essential to keep the peel stresses below the transverse tensile strength of the two adherends by using appropriate geometrical parameters and adhesive types, which offer an enhanced stress distribution in the bondline and adherends in the bonded patch design.

Bonded repairs are exposed to different environmental conditions during their service life. The long-term performance of composite bonded patches depend on the structural response of the adhesive and adherends to fatigue and environmental conditions [210–212]. When subject to cyclic loading conditions, adhesives and resins can accumulate damage (*e.g.* crazing, shear yielding, micro-cracking) near stress concentrations in bonded joints and initiate fatigue cracks [213–215]. In addition, the mechanical properties (*e.g.* elastic modulus, tensile strength) of thermosetting adhesives and resins can, in general, be considerably deteriorated when exposed to harsh environments (*e.g.* humidity, temperature), which will affect the durability of adhesively bonded joints [216–218]. The absorbed moisture can lead to both reversible and irreversible effects (*e.g.* plasticization, swelling and degradation). To ensure long-term durability of bonded repair patches, the individual and combined effects of mechanical and environmental loading must be accounted for in the design. Adhesives that are less sensitive to environmental service conditions could improve the long-term performance of bonded repairs.

10. Monitoring and automation of repairs: Reliability and repeatability

Manual composite repair procedures are prone to human error —depending on the skills and knowledge of repair technicians [91]. Human errors and inconsistencies in repair processes can significantly influence the structural strength and durability of bonded composite repairs [175]. Post-repair non-destructive evaluation of bonded patches can detect physical disbonds and voids [184], but cannot identify weak interface bonds (*i.e.* kissing bonds) introduced (*e.g.* through interface contamination or non-uniform surface treatment) during the repair [219]. Under-cured adhesive bondline and resin (with soft patches) regions are also difficult to identify. Weak interface bonds could initiate considerable disbonding of repair patches over time and pose a threat to the patch efficiency and integrity during service. In addition, without testing destructively, it is not possible to assess the bond strength of repair patches with current non-destructive techniques [220]. With these current limitations, post-repair non-destructive evaluation cannot reliably ensure the quality of bonded patches and thus cannot alone be used to accept or reject a bonded repair [219]. In this regard, especially in the area of primary structural repair, some elements of process control, quality assurance and structural heath monitoring when incorporated can provide opportunities to ensure reliability and repeatability—two critical factors for the certification of aircraft structural repairs. While automation of some of the repair processes (*e.g.* material removal, surface preparation, patch fabrication) can minimize human error and inconsistencies, condition monitoring of bonded patches by using active structural health monitoring techniques can assess structural integrity and thus ensure airworthiness.

10.1. Structural health monitoring

Bonded composite repairs require regular inspections to verify their structural performance. Non-destructive inspection techniques such as thermography, shearography and ultrasonic testing can be used in the repaired regions to assess damage. But these techniques cannot provide real-time data to assess damage and thus condition-based maintenance – instead of scheduled-based maintenance –is not possible [221,222]. Structural health monitoring of composite structures is an emerging research area with a potential for real-time monitoring to detect subcritical or critical damage in order to enhance structural maintenance and safety [223–226]. For bonded composite repairs, a health monitoring system could provide opportunities to assess the structural integrity of the patch in real-time and help schedule condition-based non-destructive inspection. But the monitoring system must have high reliability and probability of damage detection; withstand the service conditions which the bonded patch will be exposed to; minimum influence on the structural integrity of the patch when embedded; and stand alone and autonomous [227]. As surface mounted sensor systems will be exposed to harsh environmental and mechanical conditions, an embedded approach [228,229], which is often suitable for composites during processing, could be more appropriate. However, the influence of embedded sensors on the mechanical properties (*e.g.* embedded systems in bondlines could act as stress raisers similar to defects or disbonds) of bonded repair needs to be appropriately assessed.

Structural health monitoring techniques use sensors to detect small variations in signals such as strain or vibration as a result of damage initiation or propagation. For example, strain distribution near the damaged region of composite bonded joints under external load can be considerably different to that of the undamaged regions [221]. The variation in strain distributions often depend on the extent of damage and is often highly localised to the damaged regions [230]. A strain-based approach can thus be employed to assess damage by monitoring such localized strain variations (*e.g.* by strain gauges, optical fibres with Bragg grating) in real-time [231–235]. In comparison to conventional strain sensors, optical fibres with Bragg grating can offer improved mechanical and environmental durability as well as sensor networking capability [236,237]. But strain sensors need to be located near damage sensitive regions in order to measure the local variation in strain distributions. In bonded repairs, as the most damage sensitive regions are the ends of the parent-patch interface, strain sensors installed near the edges of the patch could be used for continuous monitoring. However, it is difficult to accurately characterise the extent of damage in a bonded repair by using strain sensors at discrete locations.

Ultrasonic waves such as guided Lamb waves, which can propagate large distances in plate-like structures such as composite laminates, provide broader diagnostic coverage than conventional strain sensors for active structural health monitoring of composite structures [238–242]. Lamb waves can be generated in composite structures by using an array of piezoelectric transducers, which are either surface bonded or embedded, and exciting with an alternating voltage, which produces contraction and expansion through the piezoelectric effect [243–247]. The wave reflection or diffraction, which occurs at the structural boundaries or discontinuities or damage, can thus be used for monitoring composite damage either with pitch-catch or pulse-echo modes [248]. As Lamb waves exist in symmetric and anti-symmetric modes and their interaction with composite damage is complicated (*e.g.* different Lamb wave modes propagate in the material with different velocities and thus be detected at different times), the fundamental modes are isolated and then used for monitoring structural damage [136]. As piezoelectric transducers can be embedded in bonded composite patches during patch fabrication, ultrasonic wave-based structural health monitoring could provide opportunities for assessing the structural integrity of bonded repairs. However, the geometric complexities of bonded repairs could lead to complicated wave propagation characteristics [249] (*e.g.* scattering) and consequently affect signal interpretation. The appropriate choice of the input frequency and the knowledge of the interaction between the incident stress wave and the geometrical variations are thus important. In addition, wave propagation could be influenced by the operational and environmental conditions (*e.g.* temperature and humidity) of bonded repairs [244].

10.2. Automation and repeatability

With current repair technologies, composite bonded repairs are typically conducted by trained repair technicians by using manual processes [35]. Considering the increased usage of composites in both primary and secondary structural applications, automation is likely to be a major industry requirement in order to achieve robust, reliable and repeatable bonded repairs. Structural repairs with automated processes may also help reduce aircraft downtime and consequently be cost-effective. Although automation technologies exist in composite manufacturing, it would be a tall order to fully automate bonded composite repairs, given the inevitable variability involved in aircraft structural damage and repair scenario [52]. However, automating some of the key elements involved in bonded repairs such as damage assessment, material removal and surface preparation could significantly minimize processing inconsistencies and human errors [250]. Advanced non-destructive techniques such as laser ultrasonic scanning, pulse thermography, digital shearography could offer opportunities for non-contact, fast, automated damage assessment. Non-conventional machining technologies such as pulse laser ablation and abrasive waterjet milling could allow automated machining for material removal and also improve dimensional accuracy. Surface treatment techniques such as pulse laser and atmospheric plasma processes could be automated for consistent, uniform surface properties. In addition, *in situ* spectroscopy probes (*e.g.* Fourier Transform Infrared and Raman spectroscopy), when combined with surface treatment techniques, could provide an integrated and quantitative assessment of surface properties in order to achieve consistent interface bond strengths. Furthermore, integrated analysis and design software tools, which can accurately predict the effects of machining, curing, material and geometrical factors involved in bonded repairs, based on advanced numerical modelling techniques could ensure robust and optimised repairs.

11. Conclusions

Although the composite market, in terms of material utilisation in new products, is globally growing at a healthy rate, the science and technology that support this market growth need to progress at a similar rate for sustainability. This is lagging behind at the moment. With not-fully-mature composite design rules, manufacturing processes and joining technologies, the safety and efficiency of composite aircraft will largely depend on structural maintenance and repair. In this context, research and innovation in structural repair technologies play a critical role in composite aircraft MRO, especially for repairing composite components used in primary structural applications. Structural bonded repairs (*e.g.* scarf repairs) offer enhanced stress transfer mechanisms, joint efficiency and aerodynamics. But it is essential to develop robust, reliable and repeatable bonded repair technologies in order to have certifiable and cost-effective aircraft composite repairs. There is a strong need for improving the current composite repair technologies in several key areas—advanced non-destructive testing for damage assessment; non-conventional composite machining for material removal; advanced surface treatments for interface bonding; controlled cure conditions for patch fabrication; accurate analysis and design for optimised repairs; condition monitoring and automation for reliable and repeatable repairs.

In this review, several scientific challenges and opportunities have been identified in order to develop cost-effective and certifiable composite bonded repair technologies.

- As damage mechanisms in composites are often very complex because of their inherent non-homogenous and anisotropic material behaviour, non-destructive inspection poses several challenges for accurate and reliable damage assessment. Several non-destructive testing techniques are used for different damage types, but there is no unique technique available that can accurately evaluate all damage types in composite materials. Advanced techniques such as active thermography, digital shearography and laser ultrasonics could, however, offer opportunities (Section 5) for non-contact and automatable damage assessment.
- Accurate material removal for scarf repairs requires controlled composite machining processes. Conventional machining techniques are not ideal for machining complex geometries (*i.e.* damage removal and scarfing) and could introduce material damage due to applied machining forces and tool-generated heat. Non-conventional techniques such as laser ablation and abrasive waterjet machining could, however, offer opportunities (Section 6) for developing accurate and automatable material removal processes.
- Surface preparation is essential to modify surface physical and chemical properties, increase surface energy and remove contaminants and weak boundary layers. Surfaces that are either untreated or insufficiently prepared prior to bonding could lead to parent-patch interface fracture and thus reduce the repair efficiency. A manual process could lead to non-uniform and inconsistent surface properties, and it may also contaminate the surface. Advanced surface treatments such as laser and plasma based processes could, however, enhance composite surface properties for bonding and thus offer opportunities (Section 7) for uniform and automatable processes.
- Suitable material systems and controlled curing conditions are essential to fabricate reliable repairs. The time required (which is directly related to aircraft downtime) to fabricate and consolidate bonded repairs could significantly influence the associated economical and operational aspects. The material systems that can be stored at ambient temperature and cured at low temperature, with short cycle time, could be ideal for bonded repairs, especially for *in situ* fabrication. Soft patch approaches (*e.g.* pre-preg or wet layup processes) in addition to out-of-autoclave processes and non-conventional curing techniques (*e.g.* induction) could offer opportunities for new developments (Section 8).
- The structural response of bonded repairs needs to be accurately analysed and designed to restore damaged components. Structural repairs should maximise the repair efficiency and minimise the risk of structural failure under service conditions. But the performance of bonded patches depends on several processing, material and geometrical parameters, and thus predicting the patch behaviour is complicated. Advanced computational modelling techniques (*e.g.* damage/fracture mechanics, statistical methods) could offer accurate numerical solutions for reliable and optimised repairs (Section 9). Advanced structural adhesives (*e.g.* toughened) could offer opportunities to enhance strength and long-term durability of bonded repairs.
- Human errors and inconsistencies in repair processes can significantly influence the structural strength and durability of bonded composite repairs. Post-repair non-destructive evaluation of bonded patches can detect physical disbonds and voids—but cannot identify weak interface bonds (*i.e.* kissing bonds) or under-cured regions. Without testing destructively, it is not possible to assess the bond strength of repair patches with current non-destructive techniques. With these current limitations, post-repair non-destructive

evaluation cannot reliably ensure the patch quality and thus cannot alone be used to accept or reject a bonded repair. However, certain elements of structural heath monitoring and automation, when incorporated in bonded repairs, could offer opportunities to ensure reliability and repeatability.

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