Bonded Repair in the United States Air Force and Work to Expand Future Capability

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ABSTRACT

The United States Air Force (USAF) has a long history with structural metal and advanced composites bonding for legacy platforms and has continued to embrace this technology for more recent aircraft, primarily those containing a significant amount of composite components. The mission of the Adhesives and Composites Team within the Air Force Research Laboratory's Materials Integrity Branch (AFRL/RXSA) is to provide quick reaction and dedicated materials and processes (M&P) support enabling the USAF to fully utilize and maintain adhesive and composite materials on existing and future systems. Through its systems support function, the team has significant bonded repair experience related to both depot and operational-level applications. The team also conducts limited in-house research aimed at improving bonded repair M&P and sponsors or supports the research of others related to adhesive bonding and repair. This paper will generally describe current USAF adhesive bonding practices for both metallic and composite structures, covering standard repairs and some unique repairs. Several adhesive bonding challenges faced by the USAF will be identified, including those associated with certification of safety-of-flight bonding. Ongoing and planned AFRL research efforts aimed at improving and/or expanding the scope of adhesive bonding to benefit repair, as well as certification and transition of bonded composite primary structure for future USAF aircraft and repairs, will also be discussed.

1.0 INTRODUCTION

United States Air Force (USAF) aircraft containing significant bonded structure have been in service for more than 60 years. Substantial adhesive bonding of metallic substrates, including honeycomb sandwich structure, was incorporated into the 1950s B-58 bomber design [1]. In the early 1960s, the C-141 transport aircraft was fielded with large amounts of bonded structure using relatively modern substrates and adhesives, mostly aluminum honeycomb core and aluminum skins bonded with modified epoxy film adhesives. The F-111 fighter/bomber that became operational in the late 1960s utilized a significant amount of bonded honeycomb sandwich. However, the C-5 transport aircraft introduced into the fleet in 1970 contained the greatest amount of metal-bonded structure of all USAF aircraft, incorporating more than 2,300 m^2 of adhesive bondlines associated with honeycomb sandwich and nearly 1,000 m^2 of additional metal-to-metal bonded structure [2]. Many other USAF aircraft contain metal-bonded structure, mostly notably aluminium honeycomb sandwich found in control surfaces. The amount of bonded metal structure on new aircraft has greatly declined, so most adhesive bonding other than for legacy systems is now associated with advanced composite components. Adhesively bonded advanced composite materials have been in USAF service for nearly 50 years, with sandwich structure using nonmetallic foam or honeycomb cores accounting for much of it. More extensive use of adhesive bonding is now found in remotely piloted vehicles, many of which are primarily adhesively bonded composite airframes.

Bonded repairs in the USAF naturally followed the introduction of bonded structures, with much repair bonding conducted to address damage to previously bonded structure. Most early bonded repairs involved aluminum honeycomb construction, repair of which still constitutes the greatest use of repair adhesives in the USAF, primarily due to the C-5 aircraft workload. In addition to repair of previously bonded structure, adhesive bonding has been used to repair or enhance monolithic structures on several aircraft. These repairs install bonded metal or advanced composite doublers to stop or retard fatigue crack growth and strengthen inadequate structure, such as areas thinned by corrosion. A high-visibility example of structural reinforcement occurred in the early 1970s when adhesively bonded boron/epoxy doublers were installed on most F-111 aircraft to address fatigue concerns by reducing stress levels in the wing pivot fittings' high-strength steel lower plates [3]. Bonded repairs for in-service or maintenance-related damage are also conducted. As early as the 1960s, two-part epoxy adhesives were used to bond metal and fiberglass patches to repair damage caused by small arms fire for several aircraft [4]. Finally, aircraft advanced composite structures typically require the use of adhesives to repair areas that were not originally bonded. Though composites are not subject to the same types of fatigue and corrosion issues that affect metallic structures, there are many ways damage requiring bonded repair can and does occur on composite aircraft structures, such as enemy action, adverse weather, maintenance accidents, and other mishaps.

2.0 CURRENT USAF BONDED REPAIR PRACTICES

Standard repairs for USAF aircraft are contained in the platform-specific technical orders (T.O.s) delivered by original equipment manufacturers (OEMs) for the systems. For the most part, these repairs are somewhat limited in size and specify the materials used for original construction. The extent to which these materials can be processed following OEM factory practices varies depending on several factors, including access to the repair area, available facilities/equipment, and the expertise of the repair technicians. Aircraft T.O.s may include factory processes but also typically specify alternative processes for prebond surface preparation, as well as pressure application and heating techniques to be used during adhesive and composite cure cycles. Given the number of OEMs that produce USAF aircraft and the wide variety of original materials and processes (M&P) specified, it is not surprising standard repair M&P do not exist in the USAF, though the general types of repairs specified in the various T.O.s are fairly similar.

For repairs not contained in a T.O. (i.e., beyond standard repair limits), engineering dispositions are required. For USAF commercial derivative aircraft for which Federal Aviation Administration (FAA)-type certificates are maintained, the USAF follows the FAA process for dispositioning repairs. For those aircraft maintained under a Military Type Certificate (MTC), repair of damage beyond the platform-specific T.O. limits requires design approval from the relevant systems program office. Ultimately, the aircraft's Chief Engineer has responsibility, but this person often delegates authority to others, such as the Aircraft Structural Integrity Program manager.

2.1 Repairs to Metallic Structures

The state of the art for USAF metal bonding is still largely defined by the Primary Adhesively Bonded Structure Technology (PABST) program from the late 1970s and early 1980s. The goal of the effort was to validate the concept of bonding rather than mechanically fastening large aircraft primary fuselage structure. From the M&P perspective, the program demonstrated phosphoric acid anodize (PAA) as a robust aluminum prebond surface preparation that provides superior bondline environmental durability when coupled with a corrosion-inhibiting adhesive bond primer and an epoxy film adhesive with mat carrier cloth. PABST identified tests for use in selection of M&P, recommending the wedge test (ASTM D3762 [5]) to assess moisture durability of bonded joints. The program also codified many best practices, such as the value of using Verifilm and prefitting details, as well as the need to avoid both peel loads in adhesives and the use 7000 series clad aluminum adherends [6]. Due to limitations imposed on repair bonding, especially when conducted on-component in an operational environment, some adhesive bonding best practices are difficult or impossible to implement.

The majority of USAF bonded repairs to metallic structure are still conducted to repair damaged aluminum honeycomb sandwich. The types of repairs have not changed much over the years and include repairs to address gouges, dents, and through-holes. Some require full-depth or partial-depth replacement of honeycomb core, as well as replacement of skins. The types of repairs identified in MIL-HDBK-337 [7] in 1982 are still in use today; however, M&P and nondestructive inspection (NDI) processes have evolved considerably since the time of its publication. Platform-specific T.O.s incorporate many of the repairs found in MIL-HDBK-337 and identify specific surface preparations and adhesives to be used for repair bonding on the various aircraft.

Depending on the application and aircraft, repair bonding surface preparations for metallic structure, primarily aluminum in the USAF, range from clean/abrade, which delivers poor moisture durability, to anodize processes such as PAA. Various acid etches, conversion coatings, and coupling agents are available for on-component use [8], and many of these are specified by the various platforms' T.O.s. PAA with bond primer is often used to treat doublers, patches, and other aluminum substrates that can be processed using the tank line method and is the preferred approach. To facilitate this, PAA/primed aluminum in several gages is purchased by the USAF for operational units, and depots are capable of conducting the PAA process and spraying bond primer in house. It is not unusual for one adherend in a bonded repair to be treated with PAA/primer while the metal on the other side of the adhesive is processed using a technique more suitable for on-component work.

Many different OEM-specified adhesives are incorporated into T.O.s and used by the USAF for repair. Most are epoxies, including both film adhesives and two-part pastes. Cure times and temperatures may be as specified by the suppliers, or alternative cures may be provided to allow for cure at lower temperatures and longer dwell times, which may be necessary for some repairs. Many pressure and temperature application techniques can be used and are identified in T.O.s, but the bulk of repairs at operational units employ heat blankets controlled by hot bonders to apply temperature while using vacuum bagging for pressure. At depots, when components can be removed from the aircraft and proper tooling is available, vacuum bagging in conjunction with oven or even autoclave cures is used.

Although most USAF metal bonding is mundane, there have been several notable exceptions involving installation of metal or composite doublers to address issues that require repairs well beyond standard T.O. limits. These efforts involved significant design, analysis, and testing prior to being approved and successfully implemented despite on-component bonding challenges. Two such examples are described below.

2.1.1 B-1B Dorsal Longeron Repair

Due to aircraft usage more severe than the design spectrum, the majority of the B-1B bomber fleet experienced cracks in the dorsal longerons [9]. A repair designed to allow the aircraft to meet its planned lifetime combined a bolted doubler on the inner mold line of each longeron with an adhesively bonded doubler on the outer mold line (OML). A stainless steel OML doubler just over 2 m in length and about 10 cm wide was bonded to each of the two stainless steel dorsal longerons per aircraft repaired.

Significant work was conducted to validate M&P for the unique application, including thermal surveys and other installation trials. Steel surface preparation for both doubler and aircraft structure was grit-blast/sol-gel with a waterborne, chromated bond primer. Primer was cured using heat lamps on aircraft before epoxy film adhesive was applied. Adhesive was cured using heat blankets, while pressure was applied on the early repairs using vacuum bagging and on later repairs using a positive pressure apparatus to achieve higher pressure and eliminate difficulties with installing leak-free vacuum bags [10]. Doublers were bonded to more than 60 B-1B aircraft from 2007 through 2012. Though no fasteners were installed through the doublers, fastened caps were included on both ends of the doublers to mitigate risk in the event of significant disbonds (Figure 2-1). The OML doublers have performed well in service to date and significant disbonds have not been observed.

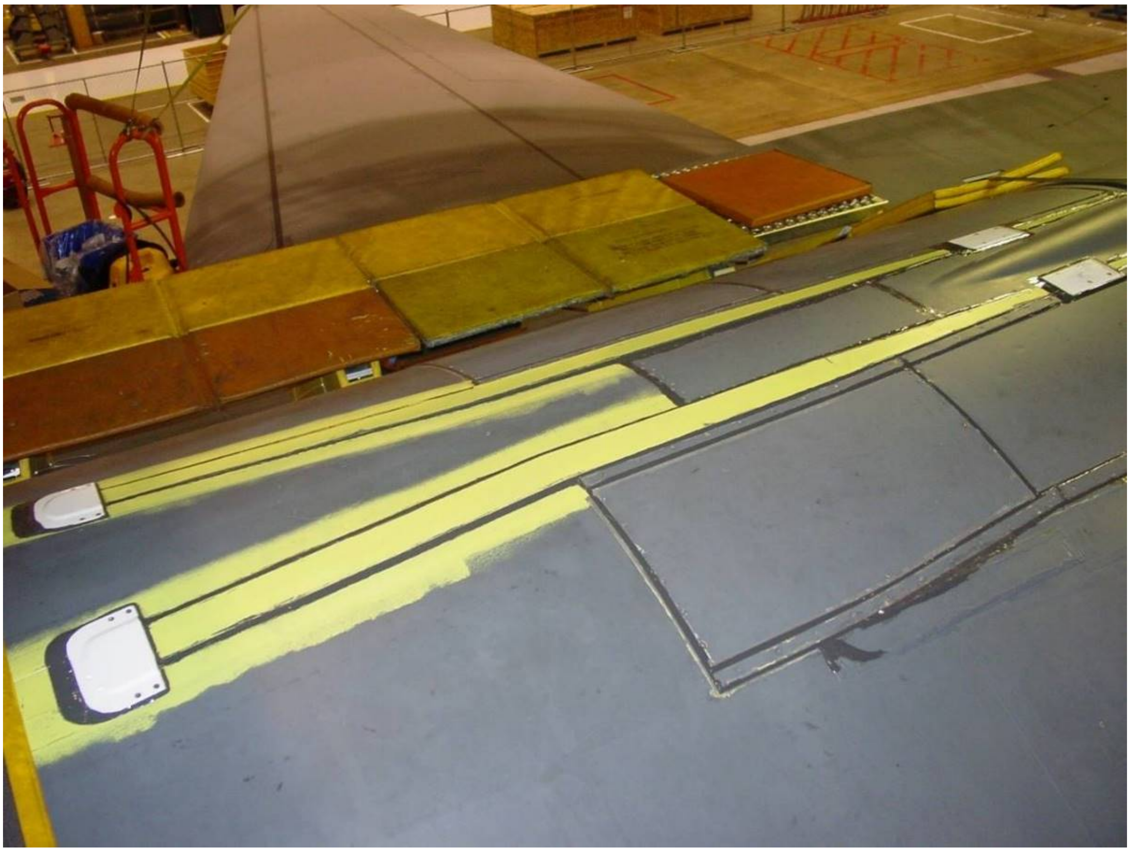

Figure 2-1: Installed B-1B Dorsal Longeron Doublers after Priming and Prior to Topcoat Application

2.1.2 Bonded Composite Repairs to Metallic Structure

Although the USAF conducted research on bonded composite repair of metal and executed limited applications prior to the 1990s, this decade saw widespread use of the technology to address aging aircraft issues. Significant applications involved F-16, C-141, and C-130 aircraft having fatigue cracking and corrosion problems [11, 12].

The most visible USAF application of this type involved repairs for cracks in 7075 aluminum lower wing skins on C-141 aircraft. Each repair required three precured boron/epoxy patches, two bonded on the inside of the wing on either side of the wing skin's integral riser, which contained the fuel "weep hole" that caused fatigue cracks to initiate, and one bonded to the OML beneath the riser. Nearly 800 repairs were made to more than 125 aircraft. In all, over 2,300 bonded patches were installed [13, 14]. For the vast majority of the repairs, aluminum surface preparation was conducted using a grit-blast/silane (GBS) process with precured adhesive bond primer [15]. The patches were bonded with standard 121 °C-curing epoxy film adhesives using electrical resistance heat blankets controlled by hot bonder units to achieve cure temperature and vacuum bags for pressure application. Considerable thermal surveys and other work were undertaken to develop detailed procedures. Heat sinks created by surrounding structure made achieving the desired cure temperature difficult, leading to temperature ranges of nearly 40 °C across some repairs. The maximum allowed temperature on the structure was 132 °C, with cure time dictated by the lowest temperature measured by thermocouples placed adjacent to the patch. In addition, confined spaces inside the wing created challenges for riser doubler bonding, and trouble containing aluminum oxide grit during blasting operations in the wing (fuel tank) putting the repairs on hold until the issue was resolved.

The C-141 repairs flew in service for about 10 years before the aircraft fleet was retired. The USAF Certification Authority supported the Air Force Research Laboratory (AFRL) and others in a project that removed bonded repairs from some of the retired aircraft to assess their performance, providing valuable data regarding bonded repair durability and the potential to influence USAF repair bonding policy if results led to increased confidence in bonded repairs [16, 17, 18]. Testing was focused on residual strength at the request of the USAF Certification Authority and included 52 repairs of cracked risers, which involved 156 patches (104 on risers that were inside fuel tanks and 52 that saw service on aircraft OMLs). Figure 2-2 shows a wing skin and outline of a typical repair specimen. The repairs were in service from as low as 2,000 flight hours to nearly 8,000 flight hours, with the average "usage age" just over 4,000 flight hours. All test specimens exceeded design limit and design ultimate stresses prior to failure, with the average residual stress at about 225% of design limit. Nine patches failed before their test specimens failed, with seven of these failing after design ultimate stress was reached. One OML patch failed at 97% of design ultimate stress due to a delamination between the two outermost patch plies, while another OML patch failed at 93% of design ultimate stress at the interface between the adhesive and bond primer. The cause for the first was a release ply left in the laminate, whereas the cause of failure for the other could not be determined. No failures occurred due to environmental attack at the metal-primer interface [19]. Data gleaned from the retired C-141 bonded repairs were generally quite positive, but these had no real effect on USAF bonded repair policy.

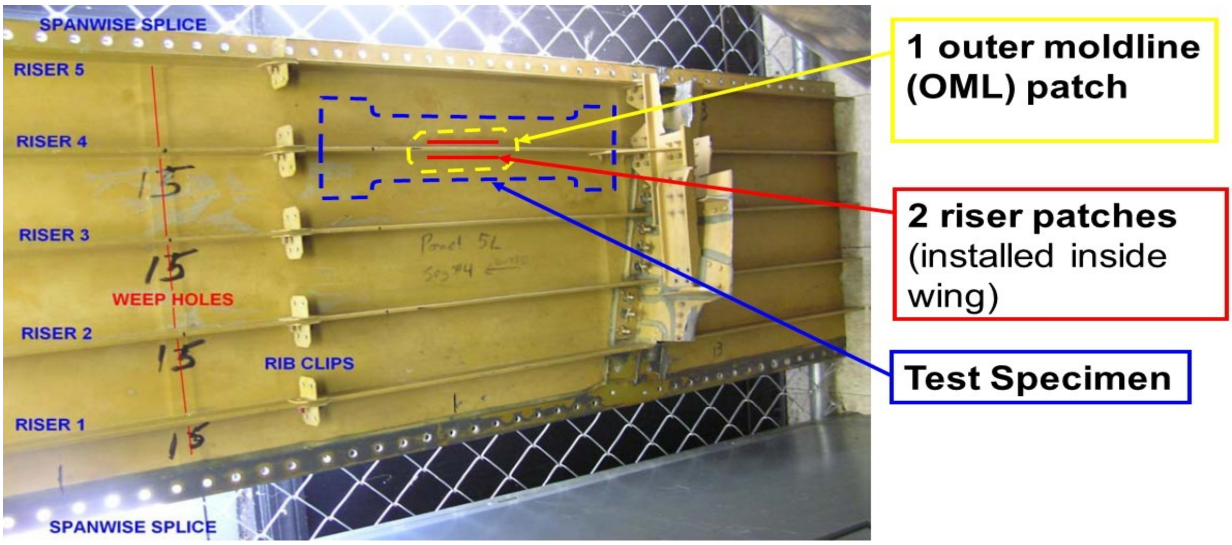

Figure 2-2: C-141 Lower Wing Skin Showing Location of Test Specimen

2.2 Repairs to Polymer Matrix Composite Structures

Unlike the case for metals, most composite repair bonding is conducted to repair damage within laminates and not previously bonded structure. Repair limits in T.O.s tend to be rather small, but larger repairs are conducted via engineering dispositions. The variety of substrates bonded is quite diverse due to the many different resin and fiber options available to OEMs for optimizing structures. Older USAF aircraft are primarily comprised of composites with epoxy matrices, whereas newer platforms also contain a significant amount of higher-temperature composite matrices, primarily bismaleimides (BMIs). Fewer thermoplastic composites are fielded, and bonded repairs to these are infrequent, especially at the operational level where it is harder to deal with surface preparation challenges. Standard T.O. repairs typically invoke OEM materials used during production. Adhesives must be compatible with matrix resins to form adequate bonds and ensure both process together properly if a cocure approach is employed. As is the case for metal bonding, all materials should be tested together to the specific requirements of the given application using the same processes and equipment that will be employed during the repair. It is assumed this is the case for T.O.-specified repairs, and it must be ensured for unique repairs, especially since these tend to involve higher risk due to size, complexity, and/or criticality.

Baseline composite repair processes are fairly mature, with platform-specific T.O.s detailing the procedures and associated M&P. The intent is to restore original component strength and/or stiffness, typically using the same composite materials and stacking sequence used to originally manufacture the component. This can be difficult, especially if maintaining OML continuity is important. Adhesive bonding is often an integral part of scarf and step repairs, whether conducted using prepreg composites or wet layups comprised of dry fabric and resins. Precured composite patches are secondarily bonded with adhesive. Surface preparation for cured composites primarily consists of cleaning and abrasion, which is acceptable for composites since these materials do not experience the moisture durability problems seen by metal surfaces treated in this way. Abrasion could be from the act of scarfing or via a separate step using abrasive papers or even grit blasting. A precured composite patch may contain a peel ply that produces a bondable surface after removal, with or without subsequent cleaning and abrasion. Also, so-called injection repairs are often implemented to “bond” delaminated or disbonded areas. Though used for metals as well, injection repairs tend to be more prevalent with composites, especially near laminate edges, including fastener holes. This type of repair can help prevent further damage and moisture intrusion, and it can often meet NDI requirements, but it is undesirable since the injected resin may not actually adhere the substrates due to the presence of contaminants that cannot be removed via proper surface preparation.

General types of repairs found in platform-specific T.O.s are documented in T.O. 1-1-690: General Advanced Composites Repair Processes Manual [20], which is managed by the USAF Life Cycle Management Center’s Advanced Composites Office (AFLCMC/EZPT-ACO). This document contains information on a large number of adhesive-related topics, including the following: composite repair methods; adhesive types and product forms; material handling, storage, and cure processes; facilities, equipment, tools, and supplies; and thermal surveys, vacuum bagging, and surface preparation. As is the case for metallic structure, most USAF composite repair bonding is routine and relatively small in scope, using established procedures. Again, notable exceptions exist, some requiring significant design, analysis, and testing to implement. Two examples are described below.

2.2.1 F-15 Vertical Stabilizer Doublers

Due to buffeting experienced in service that adversely affected fatigue life of F-15 aircraft vertical stabilizers, bonded doublers were installed on many aircraft to stiffen the structure. The design included four doublers, one on each side of both vertical stabilizers. The original procedures used to bond those doublers installed outside of the production environment led to significant bondline porosity and insufficient bond strength. Before an improved process developed by the AFRL could be implemented, other changes to the structure negated the need for the doublers. An upcoming modification, Eagle Passive Active Warning Survivability System (EPAWSS), again requires F-15 aircraft to have stiffened vertical stabilizers. This led to revalidation of the improved bonding process followed by installation of doublers on the initial EPAWSS test aircraft in 2017. A significant number of bonded doublers are expected to be installed on F-15 aircraft in support of EPAWSS.

The stiffening doublers are comprised of seven plies of precured carbon/epoxy with peel plies on their outer surfaces. The tapered doublers are about 1.5 m tall by 0.3 m to 0.7 m wide. Preparation of the doublers for bonding involves removal of the peel ply followed by light blasting with 50 micron aluminum oxide. The boron/epoxy vertical stabilizer is grit-blasted in a similar fashion after removal of organic coatings (primer and topcoat). The doublers are bonded using a two-part epoxy adhesive cured at elevated temperature using custom-designed heat blankets with vacuum bags for pressure application. Small holes in the doublers enable adhesive flow to achieve desired bondline thickness and acceptable bondline porosity but do not adversely impact doubler stiffness requirements. An installed doubler on the first EPAWSS test aircraft is shown in Figure 2-3.

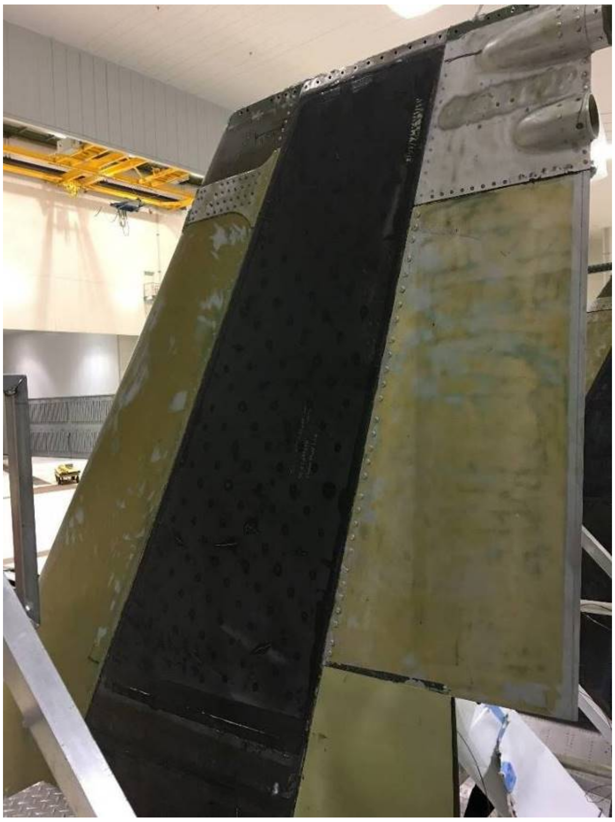

Figure 2-3: Carbon/Epoxy Doubler Installed on F-15 Boron/Epoxy Vertical Stabilizer Skin

2.2.2 Adhesively Bonded Nutplates

Adhesive bonding of nutplates, a simple concept that is relatively uncomplicated to implement, is presenting problems across a number of platforms. Though used on many metallic airframes, bonded nutplates and similar items have been increasingly utilized on composite aircraft, particularly fighters, despite previous difficulties. Bonded nutplates greatly reduce the number of holes that must be drilled in structure since rivets for nutplates attachment are eliminated, which is especially beneficial for composite structure. There are many causes for nutplate failures in service that lead directly or indirectly to failure of the bonded joint. Inadequate initial surface preparation of the nutplates (usually steel) and/or the structure (metal or composite) is only one of the issues that drive the need for nutplate repair bonding (reinstallation) on fielded aircraft. Though fairly robust prebond surface preparation processes are available for initial OEM installation, these are not typically used due to accessibility challenges and the large number of nutplates that must be bonded, which can be in the tens of thousands per aircraft. Figure 2-4 shows nutplate reinstallation (i.e., repair) and numerous nutplates in place during adhesive cure for original installation at an OEM. The colorful fixtures hold nutplates in place and apply pressure during adhesive cure; the fixtures are then removed.

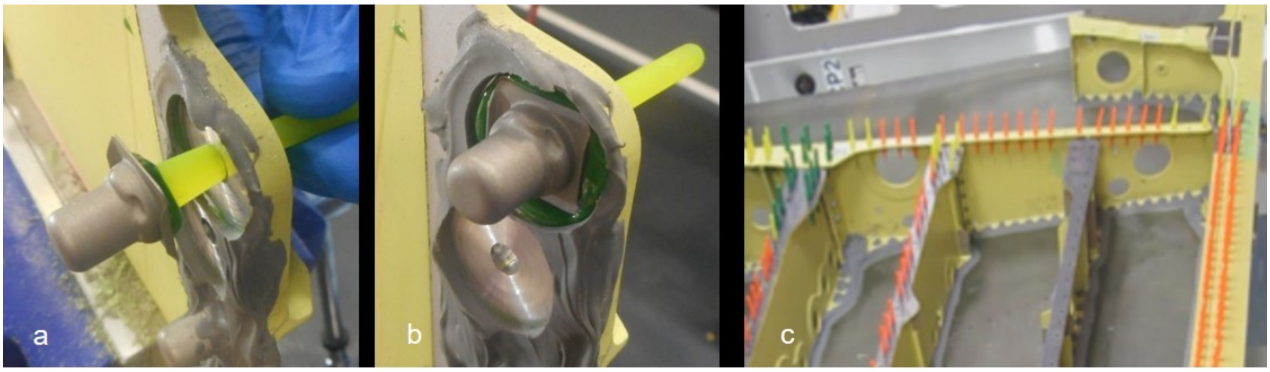

Figure 2-4: a) & b) Nutplate Reinstallation (Repair); c) Nutplates Installed and Curing (OEM)

Whatever the reason for failure, bonding new nutplates is frequently required at operational units. Challenges include removal of residual adhesive and sealant, surface preparation for new installation, and adhesive cure in a reasonable time to maintain operational capability. All of these are made difficult by limited access. Two-part epoxy and acrylic adhesives typically used for bonding can cure at ambient temperatures, but much faster accelerated cures are desired, and these require heating methods that can be used in small spaces and reliably generate the temperatures in bondlines required to achieve desired adhesive properties. Removal of residual materials can be time consuming since it must be undertaken cautiously to prevent structural damage. Torlon® cutters used on a 600 rpm drill motor are now being fielded to rapidly and safely remove residual materials. The cutters are part of a suite of removal tools developed by AFRL and the University of Dayton Research Institute, which are commercially available under the EnduroSharp™ trade name [21] and shown in Figure 2-5.

Figure 2-5: EnduroSharp™ Tools, including Cutters and Accessories for Nutplate Repair (Far Right)

3.0 REPAIR BONDING CHALLENGES

Many repair bonding challenges exist. Some are application-specific and must be adequately addressed to conduct a given repair. Other challenges include those that are more generic in nature, as well as strategic challenges that must be overcome to enable more widespread use of adhesive bonding, repair and otherwise, so the potential benefits over other fastening methods can be better realized. Many bonding challenges may also be faced by OEMs, but most of these shared problems prove to be more difficult to resolve for repair situations.

3.1 Application-specific Challenges

Application-specific challenges vary depending on the type of repair, access to the area, and capabilities of the repair facility. Obviously, repair capability at an operational unit is much different than that at a depot, so the types/sizes of repairs and the processes used will vary between these kinds of facilities. The ability to remove a component from the aircraft definitely dictates the repair processes that can be used and the likelihood an acceptable repair can be readily accomplished. Depots may be able to remove more components and even have greater capability than operational units when repairing damage in-situ, but even depot repairs are more difficult when performed on aircraft. The biggest hurdles tend to be surface preparation, along with heat and pressure application. Metal surface preparation for repair is more difficult than composite preparation since it typically involves the use of chemicals and often requires water rinsing steps. Heat and pressure application are most challenging for higher service temperature materials that require significantly elevated cure temperatures and often contain volatile components that can create bondline porosity when cured under reduced pressure. Maintaining adequate bonding conditions can also be a considerable challenge for on-component repairs, depending on the facilities available. Temperature, humidity, and airborne contaminants in the environment must be controlled to acceptable limits.

For metal bonding, inadequate surface preparation is probably the leading cause for premature bondline failure since most bonds that have failed in service have done so due to moisture attack at the metal-polymer interface [22]. Some processes, such as PAA/primer, have been shown to better resist moisture. On-component versions of the tank line PAA surface preparation were developed [8], but these are not practical for most USAF repairs and are rarely used. Although improvements to on-component prebond metal surface preparations have been made, with the USAF introducing GBS in 1993 and about 10 years later fielding simpler sol-gel processes with significantly improved wedge test performance [23], optimal surface preparation is rarely achievable for on-component work. Furthermore, preparation of both metal and composite surfaces is more difficult when repairing fielded aircraft since components are frequently contaminated by hydraulic fluids or any number of other materials. Composite repairs face an additional challenge since the structure must be dried prior to bonding to minimize porosity and ensure bondline integrity.

Unless components can be removed from aircraft and placed in proper tools, bond pressure application for repairs is challenging. It is nearly impossible to achieve the high pressures recommended by adhesive suppliers, and doing so would most likely damage surrounding structure. Positive pressure approaches can be difficult to execute over large areas, with part geometry and accessibility further complicating matters. Reduced pressure is the norm, and this can make it difficult to mate parts. The most convenient and often used technique for bonded repairs is vacuum bagging, which allows something approaching the local atmospheric pressure to be applied to the bag and underlying repair. The amount of pressure depends on the vacuum level attained (i.e., how well the bag is evacuated). Finding and repairing leaks in a vacuum bag can be a frustrating and lengthy task, especially in noisy repair environments and when many thermocouple wires and heater cords penetrate the bag to access the repair area. Excessive fasteners and other potential leak paths under the vacuum bag exacerbate the problem, particularly when backside access is unavailable. Vacuum bagging can also increase porosity in bondlines due to reduced pressure under the bag. Some adhesives, such as those containing residual solvents from the filming process, are more susceptible to porosity since the solvents tend to expand when heated. Adhesives containing entrapped air and/or moisture exhibit similar problems.

Achieving desired cure temperatures can be difficult using available means while avoiding overheating adjacent structure and overcoming heat sinks caused by that structure. Though hot air and heat lamps are often used as primary or supplemental heat sources for adhesive cure, on-component repairs most often rely on electrical resistance heat blankets controlled by hot bonders. Thermocouples are usually installed to monitor temperatures and control heaters, but verifying bondline temperatures is challenging. Thermal surveys are often necessary to ascertain proper location of monitoring and control thermocouples so these can be used during the repair to ensure temperatures meet the prescribed cure profile in the bondline, which rarely contains thermocouples. Depending on the size and complexity of the repair, many tedious and time-consuming thermal surveys may be required to determine not only thermocouple locations but also placement of heating devices, insulation, and any required cooling for sensitive adjacent areas.

3.2 Additional Challenges

Acquiring adhesives from suppliers in a timely manner has become challenging since few adhesives are now kept in stock, creating long lead times. Rather large minimum purchase requirements have also become common; these are particularly troublesome for operational units that may only require small amounts of material. These organizations often do not have adequate freezer space to store the large quantities of film adhesive dictated by supplier minimum purchase requirements, and they will often waste excess material when it cannot be used prior to expiration of its limited shelf life, especially when the testing capability for adhesive recertification is unavailable.

The USAF also faces challenges with respect to training of mechanics who conduct repair bonding operations. Though basic training and some advanced training are available, there is no standardized training or certification for those conducting bonding operations. At some operational units, repair bonding workload is not sufficient to allow mechanics to retain proficiency, and movement of personnel between locations or between assignments at a single location can also be problematic in this respect.

A large challenge facing the USAF and other organizations is determining a path to certification for adhesively bonded safety-of-flight structures for which failure of the bonded joint would result in loss of the aircraft. It is desired to use bonded joints in these types of structures, original manufacture and repair, since bonding can provide many benefits versus traditionally fastening techniques, including structural efficiency, lower weight, and lower cost. Though the PABST program made many positive contributions to metal adhesive bonding technology, it can still be considered a strategic failure since it did not lead to a change from mechanical fasteners to bonded joints in primary structure. Much of this is due to mistrust in the bond process, which is often justified by citing the many failures witnessed in service over the years, though most of these have been seen in aluminum honeycomb structure. The inability to nondestructively determine bond strength hinders efforts to establish the trust in bonded joints required to certify them for safety-of-flight structure.

4.0 BONDED REPAIRS TO SAFETY-OF-FLIGHT STRUCTURE

4.1 Current USAF Adhesive Bonding Approach for Safety-of Flight Structure

USAF adhesive bonding efforts rely on trust in the process to ensure bondlines are acceptable and will remain so for their intended lives. Many steps are taken to assure bonded joints are good, but their integrity cannot be proven with the level of certainty required to convince certification authorities to risk reliance on adhesive bonding for safety-of-flight structure. In general, best practices for adhesive bonding start with designs validated by analyses and/or testing using M&P specific to the application. Then, the integrity of the materials is checked prior to trained mechanics using them to conduct the validated processes following detailed written instructions along with some quality assurance provisions. These steps are generally supplemented by nondestructive inspections of the completed bonded joints to assure unbonded areas and porosity do not exceed acceptable limits. Depending on the application, nondestructive inspection of prebond surfaces, process control (witness) specimens, and even proof tests can be included. This approach has delivered many long-term bonded joints, but it is not foolproof. The inability to quantitatively check bond integrity after the fact is a severe limitation.

Human error and other factors can cause undesirable results even when best practices are implemented, and the risk of these occurrences prevents the USAF Certification Authority from completely trusting bonded structure. Concerns go beyond initial bond integrity, with continuing airworthiness being seen as the most difficult issue facing certification of bonded safety-of-flight structure. The lack of both validated analysis techniques and NDI capability for bond strength prevent management of bonded joints per the damage tolerance approach preferred by the USAF. Other concerns are as follows: the real probability some aircraft in a fleet will exceed design limit load in their lifetimes; aircraft usage greater than anticipated during design; extension of aircraft service life beyond what was envisioned during design; difficulty in assessing the effects of damage on residual strength; and the uncertain certification approach for structure that is overloaded or has service life extended.

Since adhesively bonded structures cannot be trusted to be adequately bonded initially and/or remain well bonded during their service life, the USAF Certification Authority follows the static strength guidance in JSSG-2006 for safety-of-flight structure that requires bonded structure be capable of sustaining design limit load with a complete bondline failure without a safety-of-flight failure [24]. This JSSG-2006 guidance does not allow a designer to take credit for a bonded-only repair. Most USAF bonded repairs, even those conducted on primary structure such as the C-141 weep hole repairs, still required inspection of the damage at intervals based on unrepaired structure and/or still had alternate load paths that prevented reliance on the repaired member for limit load capability.

4.2 Potential Future Consideration for Safety-of-Flight Bonded Repairs

Contrary to the guidance of JSSG-2006, the USAF and the United States Navy successfully operate several platforms, representing hundreds of aircraft that have originally bonded primary structure. Considering the efficiencies, it is likely future platforms will be designed with these types of structures for cost, production, and sustainment benefits, so the USAF is in the process of defining alternative methods for bonded safety-of-flight structure to comply with the aircraft structural design requirements of MIL-HDBK-516C [25]. Likewise, the USAF is in the process of defining scenarios for which credit can be taken in the future for bonded repairs to safety-of-flight structure.

The preferred USAF approach for the design of safety-of-flight structures is damage tolerance versus safe-life. The two damage tolerance approaches are fail-safety and slow damage growth. Credit for future bonded repairs to slow damage growth structures will likely be in the form of an allowance to extend inspection intervals. The inspection interval is defined as one half the flight hours (based on an assumed usage spectrum) required for a rogue flaw to grow to critical size. In order to take credit for bonded repairs for slow damage growth structures, the repair system must be sufficiently mature, there must be validated damage growth models that account for the benefits of the bonded repair, and the ability must exist to nondestructively inspect the structure through the installed repair. Repair design validation should substantiate two important elements: 1) the repaired structure meets the strength, durability, and damage tolerance requirements of the existing structure and 2) the sustainment processes and capabilities are established and documented to ensure integrity of the structure during its remaining service life.

The design of bonded repairs for use on safety-of-flight aircraft structures is predicated on, among other things, establishing the repair system is mature, which is defined by five factors [26]: 1) stable materials and material processes; 2) producibility; 3) characterized mechanical properties; 4) predictability of structural performance; and 5) supportability. The data generated and the validated analyses developed for these five factors provide the source data for the repair strength, durability and damage tolerance assessment, design, and sustainment. Since mechanical properties in bonded joints are significantly influenced by material processing, the first three factors above are related to ensuring there is a process in control. Obviously, several challenges must be met to allow the USAF Certification Authority to take credit for bonded repairs to safety-of-flight structure.

5.0 EFFORTS TO ENHANCE USAF BONDED REPAIR CAPABILITIES

The USAF and others are conducting or sponsoring efforts to improve adhesive bonding capabilities from design, analysis, and installation perspectives. Some of this work is directly aimed at enabling bonded safety-of-flight structure, while most will indirectly support this capability to some extent. Technologies delivering more robust bonding operations support this aim since they help maintain processes in control. Relevant research efforts having significant past or current AFRL involvement are described below.

5.1 Composites Affordability Initiative (CAI)

AFRL's Composites Affordability Initiative (CAI) was aimed at reducing part and fastener counts in composite structures, enabling reduced direct and indirect costs [27]. It envisioned large, integrated structures with significant adhesive bonding and recognized the need for stable processes, tools for understanding bonded composites, and quality assurance techniques for these structures. This substantial effort spanned from 1995 to 2006 and advanced several meaningful technologies that also support bonded repairs. Specifically, CAI demonstrated advantages of the structurally redundant "Pi" joint, which includes two independent bondlines and is stronger than a double lap shear joint. Use of the Pi joint was thought to be an approach for achieving significantly reduced assembly times versus traditional fay surface bonding. CAI demonstrated manufacturing of several realistic bonded structures and also highlighted the fact conventional analysis methods for bonded joints were limited in capability and accuracy. CAI advanced NDI and quality assurance tools for assessing prebond surface quality and bonded joint strength, validated improved structural analysis tools for bonded joints, and substantiated an advanced bottom-up cost model for improved accuracy in estimating costs of composite structures manufactured with CAI technologies. There were many technical successes, a large number of demonstration articles, and documented procedures on how to employ the technologies. Furthermore, there was significant interaction in the CAI program with the USAF Certification Authority at the Aeronautical Systems Center (ASC/EN), along with their Naval Air Systems Command (NAVAIR) and FAA counterparts, regarding certification methods for large integrated/bonded structures that helped reinvigorate discussions on this topic.

5.2 Transition Reliable Unitized STructure (TRUST)

The Transition Reliable Unitized STructure (TRUST) project, part of the Defense Advanced Research Projects Agency's Open Manufacturing Program, is another relatively large manufacturing-focused effort advancing technologies that will also improve repair bonding capability. The purpose of TRUST is to develop the manufacturing process control necessary for certification of unitized bonded composite primary structures without redundant fasteners [28, 29]. As the name implies, the intent is to enable trust in the bonding process. The TRUST approach is to capture shop floor variability into an informatics database that informs a probabilistic process control model that determines critical process parameters, predicts bond quality, and computes confidence to ultimately qualify the bonding process. Figure 5-1 depicts a project overview. TRUST has developed test methodologies and generated considerable data related to the effects of bond process variables on the integrity of bonded composite joints. It has also advanced several technologies, such as those for assessing prebond surface preparation adequacy, which could support USAF efforts to take credit for bonded repairs to safety-of-flight structure.

Figure 5-1: DARPA's Open Manufacturing Program - TRUST Project by Lockheed Martin [29]

5.3 Fail-Safe Technologies for Bonded Unitized Composite Structures (FASTBUCS)

AFRL's large Certification of Composites effort contains aspects that address some of the challenges facing acceptance of safety-of-flight bonded repairs. The vision of the third phase of the program, entitled Fail-Safe Technologies for Bonded Unitized Composite Structures (FASTBUCS), is to significantly reduce weight and life cycle cost of future USAF aircraft by certifying bonded unitized composite primary structures. This effort is slated to run from 2020 to 2023 and will focus on unitized structure due to the cost savings predicted by the CAI effort for this type of construction. A high-level overview of FASTBUCS showing its focus areas is depicted in Figure 5-2. FASTBUCS will leverage TRUST and ongoing AFRL efforts. The intent is to develop design and analysis tools for fail-safe bonded unitized composite structural concepts and validate these with multiple elements tests and then structural subcomponents. Another objective is to define and implement appropriate damage detection and bondline interrogation methods for composite structures with damage arrestment [30]. Despite focus on the fail-safety aspect of damage tolerance rather than slow damage growth, advancements under FASTBUCS should improve abilities to model damage growth and inspect repaired structure, which are two needs for certifying USAF safety-of-flight bonded repairs.

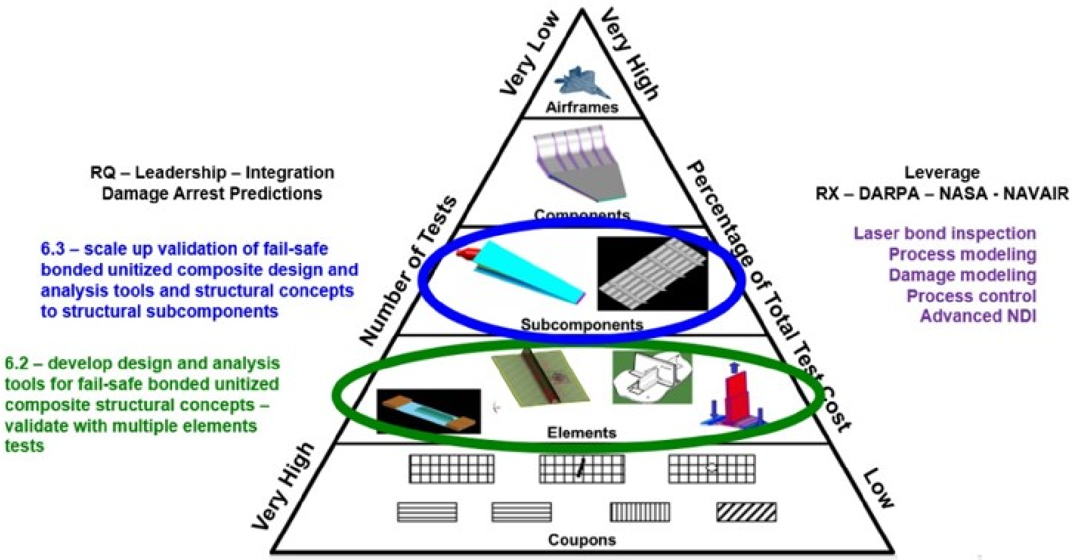

Figure 5-2: FASTBUCS Focus Areas

5.4 Low Cost Attritable Aircraft Technology (LCAAT)

AFRL's Low Cost Attritable Aircraft Technology (LCAAT) effort has the objective of developing limited function, rapidly produced, low-cost, attritable unmanned aerial vehicles to augment manned systems and is designed to address the rising cost of the USAF's sophisticated manned combat aircraft. These attritable aircraft are intended to fill a lifecycle space between sophisticated aircraft designed to last for thousands of hours and single-use systems such as missiles. The overall LCAAT program began in 2015 by conducting operational analyses, vehicle design surveys, lifecycle cost assessment, manufacturing studies, and technology gap assessments, which were performed by a combination of government and industry teams. The LCAAT concept is being validated through the low cost attritable strike demonstration (LCASD), Kratos' XQ-58A, with first flight planned for summer 2018. One AFRL LCAAT variant concept is shown in Figure 5-3. The rapid low-cost manufacturing and advanced joining aspects of the effort will have applicability to bonded repairs. Specifically, unitized assembly and novel, agile manufacturing processes are being exploited, including expansive use of primary bonded structure, moderately thick adhesive bondlines, reduced geometric complexity, and fabrication processes optimized for cost. The design, airworthiness, and service specifications and criteria are also highly tailored for attritability [31]. LCAAT's risk-tolerant approach and manufacturing concepts should further support USAF safety-of-flight bonded repairs.

Figure 5-3: AFRL Weapons Truck LCAAT Variant Concept [32]

5.5 Laser Bond Inspection (LBI)

Laser Bond Inspection (LBI) was a technology advanced during AFRL's CAI program. LBI is a post-bond inspection method providing a localized proof test that can identify (fail) weak adhesive bonds but is nondestructive to properly prepared bonds. LBI is a stress wave method that sends a controlled laser energy pulse into the structure perpendicular to the bondline. A compression wave travels through the structure and reflects off the back surface, stressing the bondline in tension as it passes through, breaking weak bonds. Traditional NDI techniques are conducted before and after the laser pulse to ascertain if the laser pulse broke weak bonds (or weak composite laminates). Engineering is required to determine laser energies for given applications, ensuring only unacceptably weak bonds fail due to the tension wave. A high peak pulse energy, short-pulse laser (5-50 J, ~200 ns) is used with a spot size of about 10 mm. The LBI device and schematic of the inspection methodology is shown in Figure 5-4.

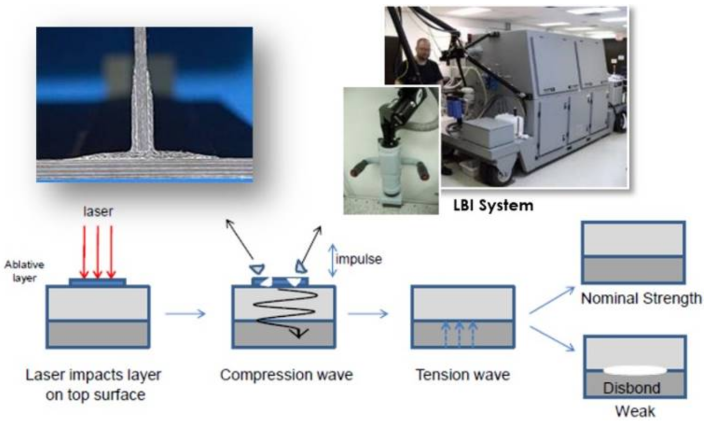

Figure 5-4: LBI Device and Inspection Methodology

AFRL is now managing an LBI validation program. Phase I, which is completed, validated LBI's ability to reliably measure composite bond strength. Three lots of panels comprised of one composite and one adhesive system were fabricated using different bond strengths and different laminate thicknesses between the adhesive bondline and surface impacted by the laser energy. Two different LBI systems were used to interrogate panels, and over 250 mechanical tests of three types were conducted. Technology gaps and desired improvements for LBI were identified, a preliminary implementation plan was drafted, and a cost-benefit analysis was completed. Phase II work, which is underway, introduced a second composite/adhesive system and is intended to develop LBI methodology and protocols for inspection of any composite material system. It will also establish inspection criteria and validate methodology for part-specific features, as well as demonstrate LBI through full-scale configured component testing with varying bond quality [33].

LBI's exact role in enabling the USAF to adhesively bond safety-of-flight adhesive bonds is not yet defined, though this type of capability has for years been believed by the USAF Certification Authority to be enabling technology for this purpose. Important considerations include the number of test spots that would need to be assessed across a bondline and whether LBI inspection would be required at intervals during service. Since concerns about degradation of composite-to-adhesive interfaces during exposure to the service environment are not nearly as great as those for metal-adhesive bonds, periodic inspection during service may not be as critical for composite joints. Current LBI efforts focus on composite-adhesive systems for both this reason and the fact future safety-of-flight bonds are expected to be focused on unitized composite structures due to anticipated structural and cost benefits. Currently, the LBI instruments cannot reach limited access areas and are relatively expensive, but ongoing and proposed work are aimed at resolving these disadvantages. LBI addresses a key technology gap associated with bonded joints, but its use for repair will likely be limited to high-value applications, such as safety-of-flight bonds.

5.6 BTG Labs Surface Analyst™ (SA)

The BTG Labs Surface Analyst (SA) had its genesis under CAI, was developed largely through efforts managed by AFRL [34, 35], and plays a significant role in the TRUST project. This commercially available instrument provides a quick means for conducting what amounts to a quantitative water-break test on surfaces to assess if they are properly prepared for adhesive bonding (Figure 5-5). Water adequately simulates a typical aerospace adhesive since both are polar molecules. A high-energy surface, typically important for bonding since it will be attracted to the adhesive, produces a smaller contact angle between the water droplet and the surface, whereas a lower-energy surface tends to produce a larger contact angle, similar to water beading on the surface of a freshly waxed automobile. The SA takes a photographic image of the surface prior to ballistic deposition of a very small drop of water via a series of microliter droplets. A second photographic image taken after the drop is deposited allows the diameter of the drop to be determined and the contact angle calculated, since drop volume is precisely known.

The instrument produces a contact angle result in a matter of about two seconds and can be used on inverted, curved, and vertical surfaces. The acceptable range of contact angles must be determined and validated using application-specific M&P and testing. Once known, the range can be programmed into the SA so a technician simply has to position the instrument over the area of interest, press a button, and wait a couple seconds for a pass or fail indication. The SA stores the results and associated images, which can also be downloaded. The relatively small tethered head allows for access to hard-to-reach areas, such as nutplate locations. The instrument provides repeatable results, is nondestructive to surfaces, and is easy to use with an Android operating system. The high-purity water canister provides about 1,000 shots, and the battery life is sufficient for practical use.

Figure 5-5: BTG Labs SA Instrument

The SA is meant for real-world production purposes and is currently used in this role by many organizations across several industries. When used to supplement a trained mechanic following validated procedures, the SA can ensure surfaces are properly prepared for bonding and document this fact. The SA can also aid in development of proper surface preparations for a specific applications, verify conditions of incoming surfaces from suppliers, determine the effect of aging of prepared surfaces, troubleshoot surface preparation processes, and aid in training of adhesive bonding technicians. The potential for the SA to benefit many repair bonding applications is apparent. It can also contribute toward establishing a process in control, which is a necessary condition for the USAF to rely on bonded repairs for safety-of-flight structure.

5.7 Ongoing AFRL Small Business Innovation Research (SBIR) Efforts

AFRL manages several Small Business Innovation Research (SBIR) efforts related to bonded repair. Established under the Small Business Innovation Development Act of 1982, the SBIR program is a competitive program that encourages domestic small businesses to engage in activities to meet specific Federally-funded Research and Development (R&D) needs [36].

5.7.1 Surface Preparation of Polymer Matrix Composites (PMCs) for Structural Adhesive Bonding

The objective of this AFRL effort was to develop a process that could prepare PMC surfaces rapidly and consistently for structural adhesive bonding. It is one of many efforts conducted by several organizations focused on energetic surface preparation techniques. Aerospace Materials Processing, LLC examined the effects of adding plasma to traditional peel ply and/or sanding methods on bonded BMI carbon fiber composites. An atmospheric helium-oxygen plasma treatment process with optimized plasma exposure time was developed, and a detailed study of the effects of surface preparation method on air-exposed and contaminated samples was conducted. Improved bond performance was observed with some BMI and adhesive systems, but a bond surface contamination investigation showed mixed results [37]. These data were then leveraged to develop atmospheric plasma for the surface preparation of tool-side BMI composites and unprimed, stainless steel nutplates with the goal of qualifying a new method for surface preparation prior to nutplate bonding. The process was shown to eliminate the inherent variability in the manual sanding process, increasing bond reliability, decreasing touch labor, and reducing scrap/rework/repair [38].

5.7.2 Thermal Modeling Based High-Temperature PMC Structural Repair

The goal of this AFRL SBIR program is to develop a repair modeling “system” that will predict thermal variations within a repair performed on-aircraft over composite or metal structures that include significant underlying substructures. It is intended to eliminate or greatly reduce the number of thermal surveys currently required to determine acceptable placement of heat sources, insulation, and thermocouples. The system will do this without detailed knowledge of the structure in the repair area and will provide the repair technician with the capability to rapidly simulate the effect of changes to the repair scenario (e.g. adding/removing heating elements or insulation) on the thermal response of the repair. Two Phase I companies, Creare LLC and Convergent Manufacturing Technologies US, Inc., envision similar concepts of operation. In these, the repair technician first performs a thermal survey of the intended repair area and immediate surrounding structure using a specialized technique/hardware developed under this SBIR program. A simplified thermal model is then created using the newly acquired thermal response of the structure. The repair technician provides input to the system specifying thermal requirements for the repair, including the acceptable temperature range, minimum isothermal soak time, and maximum acceptable temperature of the structure. The type and availability of repair consumables (e.g., insulation) and heat sources are also provided. The repair system uses the technician's input to identify scenarios with the appropriate placement of heaters, insulation, and thermocouples. Alternatively, the technician can use the guided user interface to virtually simulate alternate repair scenarios for rapid feedback. In a follow-on SBIR Phase II effort, the repair system will be demonstrated on a representative PMC aircraft structure, showing how the system is adaptable and versatile for different structures [39].

5.7.3 Direct Measurement of Bondline Temperature during Composite Repair/Fabrication

Another AFRL SBIR effort is developing improved methods to measure bondline temperature during composite material repair or fabrication without introducing critical bondline flaws or unduly increasing repair time or burden on technicians. Advanced Processing Technology (AvPro) and its partner, TSI Technologies, have developed ThermoPulse™ microwire temperature sensors placed permanently within the bondline and read remotely via low-frequency electromagnetic interrogation. The microwire sensors provide a distinguishable voltage pulse to a remote antenna whose integrated area is directly proportional to sensor temperature. More than one microwire per sensor provides self-calibration and signal normalization. Phase I evaluation of the microwire sensors and reader system proved the ability to remotely measure the temperature of a sensor permanently embedded within an approximately one-inch thick carbon fiber-reinforced polymer repair patch. In Phase II, accuracy and precision of the microwire temperature measurement will be validated, prototype interface accessories to integrate into current commercial hot bonders will be built (for closed-loop temperature control based on bondline temperatures), limited testing using composite structures similar to current aircraft composite structure/substructure will be conducted, any limitations to field the system will be addressed, and a cost benefit analysis will be performed. This technology is intended to provide increased confidence in bonded repairs by ensuring required temperatures are achieved in bondlines during adhesive cure, with sensors remaining in parts post-cure not expected to cause structural flaws [40, 41].

6.0 CONCLUSIONS

The USAF conducts bonded repairs on most aircraft types in service to repair previously bonded structure or to address issues with structure that was not originally bonded. Many composite repairs fall into the latter category, as do some unique applications for both metallic and composites structures. Most USAF repair bonding follows mature T.O. procedures using OEM-specified materials, with standard repairs tending to be rather small and/or uncomplicated while repairs specified by engineering dispositions can be of many types and sizes. Currently, following guidance provided in JSSG-2006, USAF repair bonds cannot be relied upon to carry design limit loads for safety-of-flight structure, so credit cannot be taken for the bonds and inspection intervals must be based on the unrepaired condition.

The USAF recognizes adhesive bonding can provide structural efficiencies and reduce aircraft cost. The desire for safety-of-flight bonds on future systems, especially for composites, dictates the need for a path to certification for such structures. At this time, a plan for safety-of-flight bonded repairs is being considered by the USAF Certification Authority, although some technology improvements may be required to allow the benefits of adhesive bonding to be realized as desired. The USAF and other organizations are conducting research efforts intended to improve bonded repair capabilities from design, analysis, and installation perspectives and thereby aid efforts to certify safety-of-flight repair bonds that can reduce inspection burden.

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