Certification of Bonded Aircraft Structure and Repairs

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ABSTRACT

Bonding is increasingly being used as a method for joining aircraft structure and in composite repairs. While all composite manufacturing techniques warrant close process control, structural bonds are especially critical due to the fact that their quality cannot be assured through non-destructive inspection techniques. The FAA has identified bonded repairs, sandwich structure disbond growth, and bondline quality control as risks for continued operational safety of composite structures. The FAA has also identified bonded structure as a critical item for certification efficiency, where certification methods have not been standardized. Whenever certification methods are not standardized, there exists an increased risk for an "uneven playing field" for design approval applicants, where they may be subjected to different requirements or interpretations of regulations. It is also a safety risk, where there is increased potential to miss a critical requirement during the certification process.

The FAA has published regulations and guidance documents, and is actively writing more, to ensure safety of bonded structures and repairs, including metal bonds, secondary bonds, and co-bonded structure. This paper summarizes the key considerations and expectations from published guidance in the certification of bonded structure and substantiation of bonded repairs. It also discusses related work with industry through international standards organizations.

1. CIVIL CERTIFICATION REQUIREMENTS

1.1 Regulations

The United States Federal Aviation Administration (FAA) provides several types of certifications including design and production approvals for products and articles. Relevant regulations are located in Title 14, Code of Federal Regulations (14 CFR) part 21. Several types of design approvals exist; this paper will focus on the requirements for type certification found in part 21 subpart B. For a more thorough discussion of FAA certification, see [1].

In order to certify an aircraft, engine or propeller, the applicant must, amongst other things, perform tests and analyses, provide operating and maintenance documentation, and meet the airworthiness requirements in the relevant airworthiness regulations, which are located in 14 CFR parts 23-35.

Table 1-1: FAA Aircraft Certification Regulation

14 CFR Part	Title
21	Certification Procedures for Products and Parts
23	Airworthiness Standards: Normal Category Airplanes
25	Airworthiness Standards: Transport Category Airplanes
27	Airworthiness Standards: Normal Category Rotorcraft
29	Airworthiness Standards: Transport Category Rotorcraft
33	Airworthiness Standards: Aircraft Engines
35	Airworthiness Standards: Propellers

For aircraft (including rotorcraft), the airworthiness standards have sections on General, Flight, Structure, General Design and Construction, Powerplant, Operational Limitations and Instructions. None of these specifically refer to composite materials except for one regulation in parts 27 and 29 related to fatigue and damage tolerance. In addition, relevant regulations that apply to composite structures cover static strength, materials and workmanship, fabrication methods, and material strength properties and design values. Crashworthiness, flammability, and lightning protection are other relevant subjects where composite structures may have unique means of compliance.

1.2 Guidance

The FAA publishes guidance in the form of advisory circulars, policy statements, and policy memos to provide clarification of the regulations and one or more means, but not the only means, of compliance. Applicants may follow published guidance to streamline the certification process, but are free to propose other methods.

Even though the regulations are the same for metallic or composite structures, the means of compliance to the regulations can be quite different. Advisory Circular (AC) 20-107B, "Composite Aircraft Structure," is the FAA's most comprehensive guidance for certification of composite structures. [2] The document is harmonized with the European Aviation Safety Agency (EASA) Approved Means of Compliance (AMC) 20-29 and attempts to address regulatory requirements using a safety management philosophy.

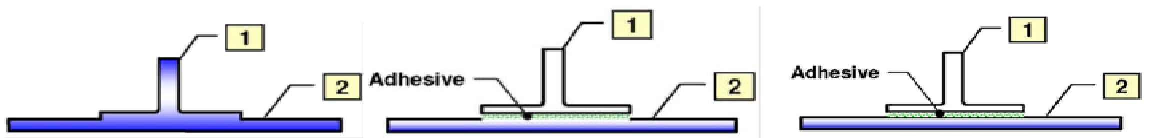
AC 20-107B describes means of compliance unique to bonded structure and is supplemented by additional policy, [3] which is applicable to part 23 aircraft, although the applicant may propose to use it for other product types. The FAA has also published research reports on the subject of bonding through the William J. Hughes Technical Center Library, which are available at https://f10011.eos-intl.net/F10011/OPAC/TileStart.aspx. Some of these reports, which are not regulatory, attempt to identify best industry practices (e.g., [4]).

The FAA is in the process of writing a new AC on the subject of bonding to document acceptable best practices for initial certification of bonded joints and the substantiation of in-service bonded repairs.

2. BONDING APPLICATIONS

2.1 Definition of a Bonded Joint

There are technically three different types of bonded joints, as shown in Figure 1 below.



Co-Curing:	**Secondary Bonding (Structural Bonding):**	**Co-Bonding (Structural Bonding):**
Components cured together - Component 1 uncured - Component 2 uncured (may include additional adhesive and/or continuous structural plies common to both Components 1 and 2)	Components bonded together with separate bonding operation - Component 1 cured* - Component 2 cured* * or metal	Components bonded together during cure of one of the components - Component 1 cured* - Component 2 uncured Or - Component 1 uncured - Component 2 cured* * or metal (may not include additional adhesive)

Figure 1. Definition of a Bonded Joint [5]

FAA guidance only recognizes Secondary Bonding and Co-Bonding as bonding processes with multiple interfaces (i.e., composite-to-composite, composite-to-metal, or metal-to-metal), where at least one of the interfaces requires additional surface preparation prior to bonding. In the case of co-curing, while an adhesive may be used between two laminates, the laminates and any adhesive are uncured and therefore do not have any surface preparation prior to bonding and cure. Sandwich structure, which consists of laminate skins bonded to a core material such as foam, metal honeycomb, or aramid honeycomb, is a specific type of bonded structure which will not be discussed in this paper.

2.2 General Aviation Applications

General aviation aircraft, which are defined as airplanes with a passenger-seating configuration of 19 or less and a maximum certificated takeoff weight of 19,000 pounds or less, have used bonded structure extensively for many years. One GA manufacturer, for example, has used metal bonding since the 1960's on secondary structure, since the 1970's on primary structure, and since the 1980's has implemented fully bonded airframes [6]. Both Cirrus and Lancair Columbia (now Cessna Corvalis) aircraft have fully bonded composite aircraft with full load transfer through thick paste adhesive joints [7, 8].

2.3 Rotorcraft Applications

Rotorcraft have two very different structural environments. Rotorcraft airframe parts see a low-cycle fatigue environment similar to fixed-wing aircraft; however, rotating parts (i.e., rotor blades) see a high–cycle fatigue environment that is unlike anything experienced by airframes. Rotor blades have utilized fully bonded structure out of necessity for decades with both metal and composite bonding; however, rotorcraft airframe parts have not had the same extensive bonding experience.

2.4 Transport Aircraft Applications

Transport aircraft tend to be the most conservative of aircraft applications when it comes to any new technologies. The corresponding load levels also pose more challenges for bonding. In addition, transport applications tend to rely on large databases of experience starting with non-critical applications and moving to critical structure. Metal bonding has been used for decades with mixed experience in primary and secondary structures, and typically utilize secondary joining with fasteners. Composite bonding was first used in lightly loaded secondary structure such as fairings and fixed panels, which filled spaces between control surfaces and other critical primary structures but bonding quickly found more critical applications in control surfaces and to attach structural stiffening elements to skin panels for the empennage. Current composite applications have bondlines that are more highly loaded, including some areas that work more of the full capability of the adhesive but most critical applications are still used to attach stiffening elements. However, most transport airplanes do not use bonding for high load transfer joints, such as exist at major fuselage splices or at the attachment of spars and skin panels for wing or empennage torque boxes. Such bonding applications are common in the general aviation world but the corresponding loads are significantly lower. Lower peel and shear load carrying capability cannot be tolerated in order to withstand fuel pressures, cabin pressures, and high shear loads resulting from heavier transport structure. [9]

2.5 Repair Applications

Bonded repairs are used across all product types to varying degrees. Most aircraft manufacturers publish maintenance instructions, which limit the use of bonded repairs because it is harder to maintain the same process controls possible in a factory.

2.6 Service Experience

While bonded joints are by and large used successfully in civil aircraft, there are several notable incidents where bonded joints have failed in service. Such failures have been the result of inadequate design, manufacturing quality control, and/or maintenance practices. Two such examples and the lessons learned are highlighted below.

2.6.1 Aloha Airlines

On April 28, 1988, a Boeing 737-200 had an explosive decompression caused by the total separation and loss of a major portion of the upper crown skin and other fuselage structure. As described on the FAA's lessons learned website [10], fuselage skin panels were bonded together with an adhesive and fastened with three rows of rivets. The fuselage pressurization (hoop) loads were intended to be transferred through the adhesive bond, rather than through the rivets.

This design used a cold bond adhesive (a scrim cloth impregnated with adhesive that cures at room temperature and must be kept refrigerated until use to prevent premature curing). The cold bond process had manufacturing difficulties (surface preparation quality, condensation in the joint during assembly, and premature curing of the adhesive). These difficulties led to the random appearance of bonds with degraded adhesion, with susceptibility to corrosion, and with some areas that did not bond at all. Disbonded areas were then subject to in-service corrosion due to moisture wicking, which led to further disbonding. Once disbonding of the lap splice occurred, the fuselage pressurization loads that were intended to be transferred by the adhesive bond were instead transferred by the rivets, which had poor design details with knife-edge features at the edge of the holes where cracks quickly formed. The sustained overload condition eventually led to widespread cracks and, eventually, catastrophic failure.

The National Transportation Safety Board (NTSB) determined that the probable cause of the accident was the failure of the Aloha Airlines maintenance program to detect the presence of significant disbonding and metal fatigue damage of the fuselage skin lap splice. After the accident, visual inspection of the exterior of the airplanes in the Aloha Airlines 737 fleet showed swelling and bulging of skin, dished fastener heads, pulled or popped rivets, and blistering, scaling, and flaking paint at many sites along the lap joints of almost every airplane. According to the NTSB, Aloha Airlines did not produce evidence that it had in place specific severe operating environment corrosion detection and control programs as outlined in the Boeing Commercial Jet Corrosion Prevention Manual. The NTSB noted that "it appears that even when Aloha Airlines personnel observed corrosion in the lap joints and tear straps, the significance of the damage and its criticality to lap joint integrity, tear strap function, and overall airplane airworthiness was not recognized..." It was further noted that "the overall condition of the Aloha Airlines fleet indicated that pilots and line maintenance personnel came to accept the classic signs of on-going corrosion damage as a normal operating condition."

2.6.2 General Aviation Wing Disbond

In December 2010 there was a significant structural disbond to a composite wing during flight. An FAA test pilot performing a production audit test flight experienced a bond failure where about seven feet of the left wing skin separated from the forward spar and damaged a fuel tank. [11] The subject aircraft is a high-performance four-seat single-engine general aviation aircraft with approximately 40-foot wingspan. It uses a significant number of composite parts and structures, including a fully bonded wing assembly consisting of two spars, numerous ribs, and sandwich construction wing skins. The pilot made a successful emergency landing.

Subsequently, the FAA issued emergency airworthiness directives grounding 13 specific aircraft. FAA investigators worked closely with the manufacturer to determine that the wing skin separated from the spar due to excessive humidity in the factory that prevented the bonded materials from curing properly. The manufacturer has since made improvements to the plant.

2.6.3 Lessons Learned

With most accidents and incidents, there is seldom a single reason for the event, but rather a confluence of conditions. The FAA and industry gained significant service experience from bonded structures put in service over time. This led to critical lessons learned, which played into current FAA guidance on bonded structures, including the following key points:

- The criticality of surface preparation and bonded process control cannot be overstated. The lack of any production-level techniques to evaluate whether or not a bond has achieved full strength necessitate the strictest of process controls for all aspects of the bonding process.
- Metal bonds will experience water ingress over time leading to local phenomena at the bond interface, often called hydration, which includes corrosion and disbonds. [4] Durability of the bonded joint must be properly assessed during certification and corrosion must be managed with maintenance actions.

3. CURRENT REQUIREMENTS AND EXPECTATIONS

3.1 Characterizing a Bonded Joint

A bonded joint is defined by five characteristics:

1. Substrate material
2. Adhesive Material
3. Surface Preparation Technique
4. Processing Methods
5. Design Details

These five factors are interrelated, and when any of them change, the joint must be re-evaluated.

Substrate materials are most easily characterized and controlled. Metal substrates typically have published design values, such as those in MMPDS [12]. Composite laminates have recommended protocols for characterization in CMH-17 and FAA publications [13-15]. In addition to chemical and physical characterization, typical mechanical properties include unnotched 0º and 90º tension and compression, in-plane shear, and short beam shear strengths as well as some notched laminate strengths.

There are no standard protocols recognized by the FAA for characterizing an adhesive material; however, the FAA is currently sponsoring research to develop such protocols. Properties may be developed at this level purely for procurement and quality control purposes, or they may be developed for analytical modelling. Typical tests include developing physical properties such as glass transition temperature, viscosity, gel time, pot life, resin flow, volatile content, and density, chemical characterization such as infrared spectroscopy, and mechanical tests such as single lap shear, flatwise tensile strength, roller peel, and fracture toughness. Exact test methods will vary based on whether the adhesive is a film or paste form.

During the process of certifying a bonded structure, surface preparation is the most significant factor in long term bond durability and is the cause of most bond failures in service [16]. Most failures are caused by ineffective processes – not just contamination. Successful bonding requires a clean, chemically active surface that is resistant to hydration. A clean surface alone is not sufficient. Common surface preparation techniques for composite substrates include removable surface plies (e.g., peel ply), hand sanding, and/or mechanical abrasion (e.g., grit blasting). Surface preparation techniques for metallic substrates depend on the metal being bonded. Common methods include etching or anodizing. These surface preparation techniques should be accompanied by cleaning procedures to prevent bondline contamination. Surface preparation definition should include evaluations on the effects of out time and shelf life on film adhesive and gel time / pot life of paste adhesive, the use of any primers, the effects of bonding environment (temperature and humidity extremes) as well as the amount of time allowed during the adhesive application process (this affects the potential formation of amine blush).

Processing methods include adhesive application methods, bondline thickness control, and cure cycle. Film adhesive application is typically more straight-forward thickness is commonly controlled with matched tooling. As with all composite materials, the cure cycle will have significant effect on the final properties of the bonded structure. Ramp rates and dwell temperature(s) affect flow and viscosity. Bonding may take place in or out of an autoclave and may or may not be accompanied by vacuum pressure. Paste adhesive processing is more complicated as unique key process parameters include:

- Mixing instructions for two part adhesives and/or with fillers
- Adhesive application – with or without a primer, shaping tools
- Thickness control/measurement, such as use of bonding rods or pre-bonding measurement techniques like verifilm or putty

However, there are some advantages to paste adhesive for filling gaps that may exist between the mating parts, assuming the structure only requires the lower strengths associated with a relatively thick and pliable bondline. Cure cycle considerations are essentially the same with paste and film adhesives, but control of outgassing is typically more critical for paste adhesives.

Lastly, the bond design affects any design values that may be assigned to the joint. Single or double overlaps, scarfed or lap joints, skin-to-stringer-type attachments all have unique design values for strength, stiffness, and durability. When the design changes, the associated design values may change, even when the material and process otherwise remains the same.

3.2 Certification Methodologies

Advisory Circular 20-107B describes two options for certifying structure – certification by test, or certification by analysis supported by test. In either methodology, it is important to remember that the FAA only certifies the "product" as a whole – the aircraft, engine, or propeller – not a bonded assembly by itself.

3.2.1 Certification by Test

In *Certification by Test*, the applicant complies with the requirements for material control and design values through lamina and laminate-level tests, which would include bulk adhesive testing. These tests are performed at extremes of the operating envelope (maximum and minimum operating temperatures, maximum humidity) to fully characterize the behaviour of the materials and ensure they are not in an operating space where strength or stiffness vary greatly as a function of temperature. In other words, the materials should be shown to be relatively stable at operating environments. The base material properties are also used to develop statistical pass/fail criteria for both batch acceptance and in-process quality assurance testing.

The next regulatory requirement is to demonstrate static strength and fatigue and damage tolerance at the full-scale level. When performing certification by test, this concept is relatively straight-forward. The various loads must be calculated and worst-case conditions applied to full-scale structure (which can be at the component level for items like landing gear, control surfaces, etc.). The challenge comes in accounting for the environmental effects and greater statistical variability of composite materials.

As the regulations are written, the maximum load ever expected in service is defined as "limit load." Limit loads must be substantiated through test where the structure must be shown to hold the load indefinitely with no detrimental damage. The regulations also define "ultimate load," which is limit load times a safety factor of 1.5. These requirements are predicated on traditional metallic behaviour, which includes a fairly low coefficient of variability in strength and stiffness. However, when greater variations are expected, such as with castings or metal fittings, additional factors of safety are required in static strength demonstrations. The regulations do not define a specific factor of safety for composites, but published guidance describes that applicants are expected to account for the greater variability associated with composites during static strength substantiations [17]. When certifying by test, this can be done by applying an overload factor to account for statistical variability that is equal to mean strength divided by A- or B-basis strength values. (The requirement for A- or B-basis values are related to whether the structure has a single or redundant load path, respectively) The mean and A- or B-basis values can be calculated from lamina- or laminate-level properties, which are considered to be conservative.

A similar overload factor can be applied to account for environmental effects by calculating the ratio of mean strength at the test condition (presumably room temperature/ambient humidity) with the worst-case strength condition (cold temperature/low humidity or high temperature/high humidity). Again, lamina- or laminate-level properties are considered to be conservative overload factors.

In both of these cases, we reference lamina or laminate properties, rather than bonded joint properties, because failures generally occur outside the bondline. When full scale failures occur in the bonded joint, appropriate overload factors will have to be calculated and applied.

3.2.2 Certification by Analysis Supported by Test

Composite structures are much more commonly certified through *analysis supported by test* utilizing a building block approach, which includes a complex mix of testing and analysis. As described in AC 20-107B [2] Paragraph 7.b, a building block approach provides for a systemic step-by-step sequence of tests and analyses progressing from the lamina level to the full-scale structure validation level. Tests and analyses at the coupon, element, detail, and subcomponent levels can be used to address the issues of variability, environment, structural discontinuity (e.g., joints, cut-outs or other stress risers), damage, manufacturing defects, and design or process-specific details. Typically, testing progresses over time from simple specimens to more complex elements and details. This approach allows the data collected for sufficient analysis correlation and the necessary replicates to quantify variations occurring at the larger structural scales to be economically obtained. The lessons learned from initial tests also help avoid early failures in more complex full scale tests, which are costlier to conduct and often occur later in a certification program schedule.

Figure 2 below has conceptual schematics of tests typically included in the building block approach for fixed wing and rotor blade structures. The large quantity of tests needed to provide a statistical basis comes from the lowest levels (coupons and elements) and the performance of structural details are validated in a lesser number of sub-component and component tests. Detail and subcomponent tests may be used to validate the ability of analysis methods to predict local strains and failure modes. Additional statistical considerations (e.g., repetitive point design testing and/or component overload factors to cover material and process variability) will be needed when analysis validation is not achieved. The details and subcomponent testing should establish failure criteria and account for impact damage in assembled composite structures. Component tests provide the final validation accounting for combined loads and complex load paths, which include some out-of-plane effects. When using the building block approach, the critical load cases and associated failure modes would be identified for component tests using the analytical methods, which are supported by test validation.

Lastly, when substantiating by analysis supported by test, design values are used that represent the worst-case environmental and statistical conditions (e.g., a B-basis design value at high temperature/high humidity conditions).

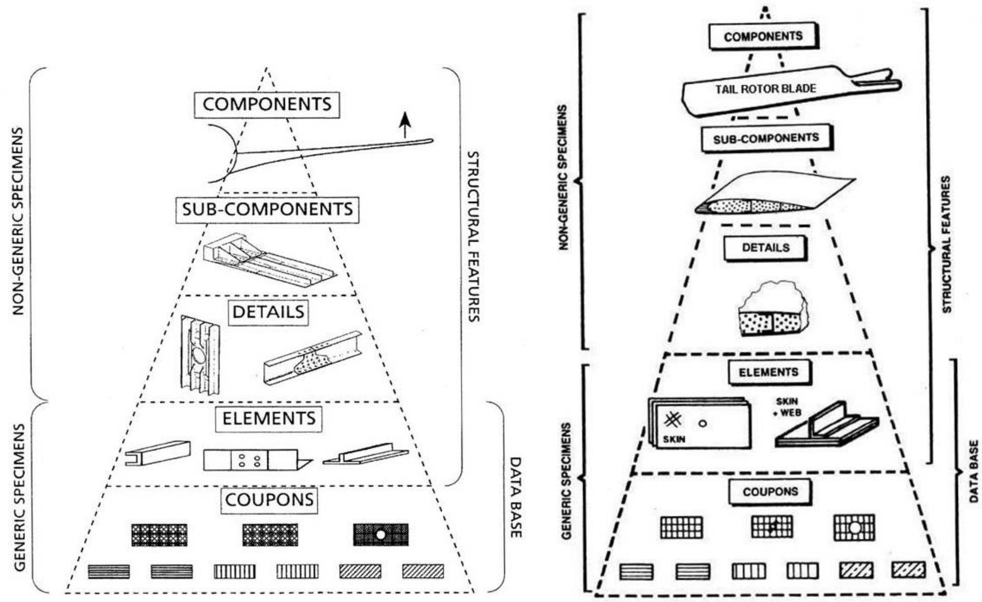


Figure 2. Building Block Approaches for Fixed Wing Aircraft and Rotorcraft [1]

3.2.3 Fatigue and Damage Tolerance Options

It is well understood that commonly used structural composite materials do not form cracks in a method similar to metals, where crack length progression correlates to a slow degradation of strength over time. Instead, composites demonstrate an instantaneous loss of strength associated with impact damages or other inherent defects. Because of this behaviour, damage tolerance evaluations begin with a damage threat assessment. Manufacturing defects and potential service damages are identified and categorized according to their probability of occurrence and their level of detectability.

Damages that are allowed in production (e.g., some level of porosity, voids, delaminations, disbonds, etc.) and damages caused by frequent, relatively low, impact energies that cause barely visible damage, are called Category 1 damages. They are substantiated for a lifetime of cycling (cycles are defined at the product level) and environmental exposure, and shown to withstand ultimate load. In other words, these damages are certified to always be present. This is very different than the fatigue substantiation philosophies for metallic structure when any known cracks are immediately repaired and after a lifetime of service (cycling and environmental exposure), are only required to demonstrate limit load capability.

Damages that are less likely to occur, and will be found during a dedicated inspection, are called Category 2 damages. These damages are cycled for two times the inspection interval and demonstrated to hold limit load. Category 3 damages are those that are readily apparently within a few flights of occurrence. They need not be cycled but must be shown to hold limit static load. Category 4 damages are those that are known to the pilot at the time of occurrence (e.g., lightning strike, rotor burst, etc.) and the structure must be shown to hold “get home” static loads (generally 75% of limit load).

For Category 1 and 2 damages that are cycled, AC 20-107B [2] provides three options for compliance with regulatory fatigue and damage tolerance requirements – no growth, slow growth, or arrested growth.

- In the *no growth* option, damage is shown to not grow during required cycling.
- *Slow growth* certification requires slow, stable, and predictable damage growth within inspection intervals. Inspection intervals and methods must be established to ensure that the damage is detected with a high probability before the residual strength drops below limit load. Once damage is detected, the structure is repaired or replaced to restore ultimate strength.
- *Arrested growth* is when damage growth is mechanically arrested or terminated before the residual strength drops below the critical threshold. As with slow growth scenario, arrested growth must be slow, stable, and predictable so that the inspection interval can be defined. This method requires statistically significant test demonstration to ensure that the residual strength of the structure is above the critical threshold, including environmental effects. The damage growth must also be readily detectable with the prescribed inspections. The arrestment method must be shown to be repeatable and reliable in all critical loading conditions.

Both slow growth and arrested growth options applied to composite aircraft structures are similar to the normal crack-growth management method for metal structures. Most airframe applications are certified for no growth. However, some high-cycle applications such as rotor blades and engines, are certified for slow or arrested growth.

The culmination of fatigue and damage tolerance substantiation is a set of maintenance instructions (e.g., inspection intervals and replacement times). For Category 1 damages that demonstrate ultimate load capability after fatigue life, the outcome is a reliable demonstration of <u>replacement time</u> (i.e., flaw tolerance / safe life demonstration). For damages that are shown to be damage tolerant with no growth, slow growth, or arrested growth, the outcome is a reliable demonstration of <u>inspection intervals</u>.

3.3 Bonded Structure Certification

Certifying a bonded joint consists of more steps than characterizing an adhesive or performing lap shear coupon tests. It is a combination of controlling the raw materials involved in the bonding process, controlling the process, developing design allowables, substantiating the structural strength, and substantiating fatigue and damage tolerance behaviour supplemented with appropriate maintenance instructions.

There are four steps to certify a bonded structure, plus one additional expectation.

3.3.1 Screening Tests

Screening tests are not required but are best practices to ensure the bonded structure will be successful. Unless the applicant has a history of successful bonding (for example, in a non-certified product), the combination of adhesive, substrate, surface preparation, and processing should be investigated to ensure sufficient adhesion and long term durability.

Screening tests should ensure adhesive/substrate compatibility. No standard protocols yet exist for this process; however, acceptable methods can include ensuring chemical compatibility, performing rheology studies (if cocured bond), microscopic inspections for voids or porosity, and mechanical tests for Mode 1 tension (cleavage).

Bonds must be shown to be durable at operating environments. Coupon-level tests are appropriate for screening tests to ensure the bond will be successful or they may be used as part of the building block approach. However, lap shear tests per ASTM D1002 [18] are ineffective for demonstrating bond durability. While that is an appropriate test for quality assurance, lap shear will not validate long term bond durability. A wedge test, such as ASTM D3762 [19] for metallic substrates, has been shown to be an effective measure of durability with the ability to predict long term performance with appropriate pass/fail criteria. One criteria the FAA has accepted to substantiate metal bond durability under ASTM D3762 is:

- Less than five percent adhesion (interfacial) failure and
- Crack growth during exposure does not exceed 0.20 inch in 24 hours of exposure, or 0.25 inch in 48 hours of exposure. [4]

All screening tests should ensure failures do not occur in the bondline, as this indicates a lack of proper adhesion between the substrate and adhesive.

3.3.2 Characterize Substrates

The substrate materials must be fully characterized. This is typically straight-forward for metallic substrates where industry standards and published design values are an acceptable means of compliance [20, 21].

For composite materials, this step includes development of a material specification, process specification and material design values. Published protocols exist for generating this data for common material forms [13-15, 22, 23].

3.3.3 Characterize Adhesive

As with composite substrates, this step consists of developing a material specification, process specification and material design values. The design values are required for quality assurance purposes, but may be used in some analytical methods. No guidelines currently exist within the aviation industry for what tests should be performed to characterize an adhesive. Each applicant has proposed their own test matrix with a combination of chemical physical, and mechanical properties. The number of tests must be statistically significant and they must characterize the adhesive for all environmental effects. These tests may be performed on substrates other than those used in the final bonded joint, if the test failures occur in the adhesive itself.

3.3.4 Characterize Bonded Joint

While the bulk adhesive properties rely on raw material procurement standards and process/cure control, properties associated with a bonded joint are more complex as they also rely on substrate controls, surface preparation, and design features.

This step begins with definition of all critical process steps in a process specification. Bonding processes must be repeatable and reliable. Processes should be vetted for all corners of the processing envelope. Applicants must understand the sensitivity of structural performance based upon expected variation permitted per the process. Characterization outside the process limits is recommended to ensure process robustness. A “process control mentality,” which includes a combination of in-process inspections and tests, has proven to be the most reliable means of ensuring the quality of adhesive bonds. Some key bond fabrication process considerations requiring close control include material handling and storage; bond surface preparation; mating part dimensional tolerance control; adhesive application and clamp-up pressure; bondline thickness control; bonded part cure (thermal management); cured part inspection and handling procedures; and bond technician training for specific material, processes, tooling, and equipment.

The process conditions that produce the least conservative structure that will be allowed in production should then be demonstrated for static strength. As described in Section 3.2.1, this may be performed at the full-scale level. However, most applicants will do this through analysis supported by test. Lap shear stiffness and strength are common mechanical tests for adhesive and bond process qualification. Shear tests do not provide a reliable measure of long-term durability and environmental degradation associated with poor bonding processes (i.e., lack of adhesion). Some type of peel test has proven more reliable for evaluating proper adhesion. Without chemical bonding, the so-called condition of a “weak bond” exists when the bonded joint is either loaded by peel forces or exposed to the environment over a long period of time, or both. Adhesion failures, which indicate the lack of chemical bonding between substrate and adhesive materials, are considered an unacceptable failure mode in all test types.

Lastly, the bond must be substantiated for fatigue and damage tolerance. Full scale testing is an option provided all impact damages, environmental effects and load conditions are accounted for (including thermally-induced loads). The difficulty lies in two areas. First, it is impossible to correctly apply thermal loads, which act in opposite directions for any metal/composite interface, to structure without placing the joint in a hot or cold environment. Secondly, the effects of environmental aging, which include hydration, are typically impractical to apply at the full scale. For these reasons, at least portions of the fatigue and damage tolerance evaluation are performed at lower levels of the building block.

3.3.5 Section 23.573(a)

Title 14 CFR 23.573(a) set forth requirements for substantiating the primary composite bonded joints for damage tolerance and fatigue. This rule applies to small aircraft with a certification basis of Amendment 63 or earlier. At Amendment 64, effective August 30, 2018, the prescriptive nature of this rule was replaced with performance-based standards. Applicants are allowed to continue to use these prescriptive means of compliance to the new regulation. In addition, although this was a small airplane rule, the same performance standards are normally expected with transport and rotorcraft category aircraft.

The regulation § 23.573(a)(5) states in part: "*the failure of which would result in catastrophic loss of the airplane, the limit load capacity must be substantiated by one of the following methods—(i) The maximum disbonds of each bonded joint consistent with the capability to withstand the loads in paragraph (a)(3) of this section must be determined by analysis, tests, or both. Disbonds of each bonded joint greater than this must be prevented by design features; or (ii) Proof testing must be conducted on each production article that will apply the critical limit design load to each critical bonded joint; or (iii) Repeatable and reliable non-destructive inspection techniques must be established that ensure the strength of each joint.*"

Most applicants choose to have bondline redundancy identified in option (i) such that if the bondline fails between arresting features, the remaining structure will hold limit load. (The structure must hold ultimate load with the bond intact.) A few applicants have selected to use limit load proof testing of each article. This has been acceptable for some less critical structures. The third option has yet to be successfully demonstrated. There are currently no non-destructive inspection methods that can assure a full strength bond. Current methods are limited to finding physical features such as porosity, voids, and disbonds, but are not able to detect weak bonds such that may exist from undercure or the presence of amine blush or other contaminants.

Note none of these options are in lieu of the qualification process described above, including close control of the bonding process overseen by rigorous quality control. Fail safety implied by the first option is not intended to provide adequate safety for the systematic problem of a bad bonding process applied to a fleet of aircraft structures. Instead, it gives fail safety against bonding problems that may occasionally occur over local areas (e.g., insufficient local bond contact pressure or contamination). Performing static proof tests to limit load may not detect weak bonds requiring environmental exposure and time to degrade bonded joint strength. This issue should be covered by adequately demonstrating that qualified bonding materials and processes have long-term environmental durability. Finally, the third option is open for future advancement and validation of non-destructive inspection (NDI) technology to detect weak bonds, which degrade over time and lead to adhesion failures.

3.4 Bonded Repairs

Bonded repairs have their own set of considerations. They are preferred in service over bolted repairs for their superior load transfer and aerodynamically flush surface although they have some drawbacks as well, such as large area requirements for scarf distances. All bonding repair processes must be defined and qualified following similar procedures and considerations as initial certification. There are several additional considerations that are unique to bonded repair.

1. Few standard practices for repair designers or repair technicians.
2. Materials and processes are different between manufacturers.
3. Repair technician training is not standardized.
4. Repair design is extremely difficult without a knowledge of base structure materials, processes, and design philosophy.
5. Reverse engineering techniques are not mature.
6. Repairs are typically performed in less controlled environments than initial manufacturing.

The FAA has documented case studies of inadequate bonded repairs and considers this to be a significant safety risk. [24] One mitigating action has been to publish a policy on bonded repair size limits. [25] The policy requires that repair processes produce a consistently sound structure and be performed under an approved process specification using approved and qualified repair materials with structural substantiation to ultimate load based on tests or analysis supported by tests. Furthermore, it requires that the bonded repair be designed such that if the bond fails between arresting features, the remaining structure can hold limit load. Data supporting the bonded repair must include inspections that are capable of detecting complete or partial failure of the bondline between arresting features. Additional discussion on the background leading to the policy can be found in [26].

4. FUTURE WORK

The FAA is sponsoring and supporting significant work on bonded structures. The FAA has issued numerous research grants for subjects including: adhesive characterization protocols, bonded joint evaluation protocols, developing test methods for Mode 1 cleavage and Mode 2 shear, investigation of peel ply influences, and adhesive substrate compatibility protocols.

Within industry, the FAA is heavily involved in developing new content for CMH-17 Volume 3 Chapter 14 on substantiation of bonded repairs, as well as other CMH-17 sections on bonding protocols. The SAE commercial aircraft composite repair committee (CACRC) has already published numerous standards for repair technician training and repair processes and continues to write new standards.

All of the mentioned research and industry documentation will support a new FAA advisory circular on bonded structure to include recommendations for initial certification protocols that promote standardization and bonded repair best practices to promote safety. This new guidance is planned for publication in 2021.

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