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Memorandum

Subject: **INFORMATION**: Bonded Joints and Structures - Technical Issues and Certification Considerations; PS-ACE100-2005-10038

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1.0 General

Many manufacturing and repair applications for aircraft structures in small airplanes, transport airplanes, rotorcraft, and propellers use bonding. Many technical issues for bonding are complex and require cross-functional teams for successful applications. Government agencies and the aircraft industry combined their adhesive bonding experiences and technical insights to gain mutual safety benefits. In 2004, the FAA conducted a survey and two workshops to benchmark industry practices for structural bonding.

In general, bonded structures may include composite-to-composite, composite-to-metal, and metal-to-metal. The nature and technical parameters that govern these three types of bonded structures are, in essence, the same or closely related. This policy statement is applicable to these three types. Both manufacturing and maintenance (repair) can use structural bonding applications.

1.1 Purposes and Scope

Building on data collected through the survey and workshops, the Small Airplane Directorate developed this policy statement. The purposes of this policy statement include: (1) to review the critical safety/technical issues, (2) to highlight some of the successful engineering practices employed in the industry, and (3) to present regulatory requirements and certification considerations pertinent to bonded structures. This policy statement also identifies some available guidance and technical resources for reference purposes. This policy statement applies to part 23 airplanes.

To achieve continued operational safety, the bonding applications require integrated considerations involving design, manufacturing and maintenance. The scope of this policy statement includes (1) material and process qualification and control, (2) design development and structural substantiation, (3) manufacturing implementation, and (4) repair implementation.

Section 3 identifies key technical issues for bonded structures. Section 4 addresses specific certification considerations for the same technical issues, providing regulatory policy for bonded structures. Section 3 also summarizes some proven engineering practices used to address the key technical issues for bonded structures. Consider such information as guidelines or recommendations, which are documented in greater detail in an FAA Technical Report [DOT/FAA/AR-05/13].

1.2 Bonded Structure Applications

Traditionally, the general aviation (small airplanes) industry often led in developing bonding applications. These applications extended from metal bonding in primary load bearing applications to the extensive use of composite bonding in new prop-driven airplanes (for example, sandwich skin panels, attachments and major splices). Transport airplanes widely employed bonded attachments for some metal and most composite structures (for example, stringers and sandwich panels). Rotorcraft and propellers used bonded structures in some airframe and dynamic parts (for example, rotor blades and propellers have bonded metal and composite structure). For maintenance functions, bonded repairs are typically used with sandwich panels for all types of products.

Using bonded structure has advantages such as cost saving and weight reduction; therefore, new applications are expanding and challenging the qualified workforce. Development of guidance and training is a high priority to maintain the required level of aviation safety both for initial and continued airworthiness.

The application criticality of bonded structures may be assessed by a few key parameters. These parameters include (1) structure function/configuration (for example, primary versus secondary, single versus multi load path), (2) loading types/characteristics, (3) environment of operation, and (4) service experience. In general, more critical applications require more stringent process control and substantiation for ensuring structural integrity.

1.3 Composite Safety and Certification Initiatives

In 1999, the Federal Aviation Administration (FAA) established the Composite Safety and Certification Initiatives (CS&CI) program for work with industry, government agencies, and academia to update certification guidance materials and support standardized composite engineering practices. To support this mandate, the Small Airplane Directorate has developed several guidance materials through the years. The guidance includes "Materials Qualification and Equivalency (Policy, 2003)," "Static Strength Substantiation (Policy, 2001)," "Substantiation of Secondary Composite Structures (Policy, 2005)," and "Acceptance Guidance on Material Procurement and Process Specifications (AC, 2003)." These guidance materials are listed under Sections 2.2 and 2.3.

Under CS&CI, a parallel effort was also performed in the Rotorcraft Directorate. From 2000 to 2002, Aviation Rulemaking Advisory Committee (ARAC) efforts for a new rule (i.e., Sections 27.573 and 29.573) and advisory circular materials were conducted. This activity resulted in an updated AC 29-2C-MG 8 (2005). In this AC, process quality control is highlighted as a primary focus to ensure the long-term performance of bonded joints. Additional thoughts on bonding are also presented therein.

An international working group under "The Technical Cooperation Program (TTCP)" drafted a "Certification of Bonded Structure" document in 2001, following three years of coordinated efforts. This document provided a good basis in general guidance for certification and recommended future industry interface to establish more guidance. We followed this recommendation in defining the FAA's industry survey and bonded structures workshop as outlined below.

1.4 Industry Survey and Bonded Structures Workshop

In 2004, tasks were initiated to benchmark industry practices for structural bonding. The efforts included a survey and two bonded structures workshops (June 2004 in Seattle, Washington and October 2004 in London, United Kingdom) to engage experts from around the world. These efforts addressed the full scope of the continued operational safety. Technically, it covers (1) material and process qualification and control, (2) design development and structural substantiation, (3) manufacturing implementation and experience, and (4) maintenance implementation and experience. FAA Technical Report [DOT/FAA/AR-05/13] documents the results of these efforts.

The bonded structures survey and workshops resulted in a large amount of data to benchmark industry practices. This information forms the technical foundation for this policy statement.

2.0 Regulations, Guidance and Supporting References

2.1 Federal Regulations

The regulations closely related to this policy statement include:

14 CFR Part 21, Subpart G - Production Certificates

Section 21.139	Quality control.
Section 21.143	Quality control data requirements; prime manufacturer.
Section 21.147	Changes in quality control system.

14 CFR Part 23, Subpart C – Structure

Section 23.305	Strength and deformation.
Section 23.307	Proof of structure.
Section 23.573	Damage tolerance and fatigue evaluation of structure.
Section 23.575	Inspections and other procedures.

14 CFR Part 23, Subpart D - Design and Construction

Section 23.601	General.
Section 23.603	Materials and workmanship.
Section 23.605	Fabrication methods.
Section 23.609	Protection of structure.
Section 23.611	Accessibility provisions.
Section 23.613	Material strength properties and design values.
Section 23.865	Fire protection of flight controls, engine mounts, and other flight structure.

14 CFR Part 23, Subpart G - Operating Limitations and Information

Section 23.1529	Instructions for Continued Airworthiness.

14 CFR Part 43 - Maintenance, Preventive Maintenance, Rebuilding and Alteration

Except for § 23.573(a), these regulations are generic in nature and applicable to both metal and composite structure. Section 23.573(a) sets forth the requirements for substantiating the primary composite airframe structures, including considerations for damage tolerance, fatigue, and bonded joints. For any bonded joint, § 23.573(a)(5) prescribes that "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."

2.2 Advisory Circulars

The following advisory circulars (ACs) relate to this policy statement. They are available on the Internet at www.faa.gov or you may request a copy at no cost from the U.S. Department of Transportation, Subsequent Distribution Office, Ardmore East Business Center, 3341 Q 75th Avenue, Landover, MD 20785.

AC 20-107A	"Composite Aircraft Structure" (April 1984)
AC 21-26	"Quality Control for the Manufacture of Composite Structures" (June 1989)
AC 23-20	"Acceptance Guidance on Material Procurement and Process Specifications for Polymer Matrix Composite Systems" (September 2003)
AC 145-6	"Repair Stations for Composite and Bonded Aircraft Structure" (November 1996)

2.3 Policy Statements

The policy statements closely related to this policy include:

“Policy on Acceptability of Temperature Differential between Wet Glass Transition Temperature (Tgwet) and Maximum Operating Temperature (MOT) for Epoxy Matrix Composite Structure” PS-ACE100-2-18-1999, February 1999

"Static Strength Substantiation of Composite Airplane Structure" PS-ACE100-2001-006, December 2001

“Material Qualification and Equivalency for Polymer Matrix Composite Material Systems" PS-ACE100-2002-006, September 2003

“Substantiation of Secondary Composite Structures" PS-ACE100-2004-10030, April 2005

The policy statements are available on line at www.faa.gov or you may request a copy from the Small Airplane Directorate at 901 Locust, Room 301, Kansas City, MO 64106.

2.4 Supporting References

The FAA Technical Center publishes the following technical reports, and they are available through the National Technical Information Service (NTIS), Springfield, Virginia 22161. They are also available in Adobe Acrobat portable document format (PDF) at the FAA William J. Hughes Technical Center's Full-Text Technical Reports page: actlibrary.tc.faa.gov.

"Certification Testing Methodology for Composite Structures, Volumes I and II" DOT/FAA/CT-86/39, October 1986

"Handbook: Manufacturing Advanced Composite Components for Airframes" DOT/FAA/AR-96/75, April 1997

"Advanced Certification Methodology for Composite Structures" DOT/FAA/AR-96/111, April 1997

"Effects of Surface Preparation on the Long-Term Durability of Adhesively Bonded Composite Joints" DOT/FAA/AR-03/53, July 2003

"Bonded Repair of Aircraft Composite Sandwich Structures," DOT/FAA/AR-03/74, February 2004

"Assessment of Industry Practices for Aircraft Bonded Joints and Structures," DOT/FAA/AR-05/13, July 2005

The Department of Defense (DOD) and the FAA jointly maintain MIL-HDBK-17. The industry has helped to develop MIL-HDBK-17. The handbook provides guidance for composite applications, and has three volumes of information on polymer matrix composite (PMC) materials. The current PMC handbooks are at Revision F (Year 2002). Volumes 1, 2, and 3 contain valuable information closely related to this policy statement. This handbook can also serve as a reference for most of the terms used in this document. You may either get MIL-HDBK-17 from the Department of Defense Single Stock Point (DODSSP), 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111, or buy this handbook through ASTM International's website at "www.astm.org" [note: search using keyword "MIL-17"].

Consistent and repeatable industry engineering practices would help to assure compliance with the requirements related to bonded joints and structures. MIL-HDBK-17, ASTM International, and Society of Automotive Engineering (SAE International) Aerospace Materials Specifications (AMS) Committee P-17 are jointly pursuing standardization. The SAE Commercial Aircraft Composite Repair Committee (CACRC) has also been a partner in standardizing engineering repair and maintenance procedures. For example, the CACRC has published "Design of Durable, Repairable, and Maintainable Aircraft Composites," (SAE AE-27, 1997).

3.0 Technical Issues

Key technical issues for bonded structures are complex and depend on many factors. As a result, successful applications rely on coordinated engineering work, which crosses several disciplines including material, process, design, analysis, manufacturing and repair. Much of the complexity relates to the bonded interface between substrate and adhesive materials. Consider this interface a unique material because the substrate is altered by the selected surface treatment to chemically bond to the adhesive during cure. Surface treatments also remove or abrade the substrate to increase the surface area for mechanical interlocking with the adhesive. As with any material or process used in aircraft structure, the goal is to develop controls that yield a bond with reliable and repeatable performance. In general, the material and process controls for bonding are more stringent than those for other fabrication processes.

Materials and processes used in bonding meet qualification standards related to structural integrity and long-term durability. Once qualified, material and process controls are used to ensure these standards are met in subsequent production and maintenance activities. Recognition of the load paths and local stress distribution is needed to design bonded joints, attachments or repair details that will meet load and environmental requirements without significant degradation over time. Manufacturing, tooling and maintenance considerations are also important to design. Bond process scale-up, design data development, and structural substantiation are coordinated for proof of concept during certification. Ultimately, bonding procedures, process controls, documentation, and training are implemented in either manufacturing or repair, or both, to reliably produce the proven structural concept.

3.1 Material and Process Qualification and Control

Qualification demonstrates the stiffness, strength, durability and reliability of bond materials and processes for aircraft applications. Such efforts start with defining bonding processes and selecting compatible substrate, adhesive, and ancillary materials.

Qualification tests are carefully selected to evaluate structural performance, environmental effects and long-term durability. In coordination with qualification, it is also important to establish (1) processing tolerances, (2) material handling and storage limits, and (3) key characteristics and process parameters to monitor in quality control. Most bond failures and problems in service have been traced to invalid qualifications or insufficient quality control of production processes.

Adhesive and substrate material selections should consider the bonded joint design configuration, loading requirements, manufacturing process constraints, environmental conditions and chemical resistance to fluids found in service. Reduction in strength properties at the maximum operating temperature (MOT) should be known for each application. The properties of polymer composite substrate and adhesive materials are affected by both temperature and moisture content, with a significant decrease in strength above the wet glass transition temperature (T_{gwet}). A simple guideline often used in selecting composite substrate materials is for the T_{gwet} to be 50 °F greater than the MOT of structural applications. The analogous guideline for adhesive materials is for the T_{gwet} to be 30 °F greater than the MOT. As discussed in the ACE-100 1999 Policy Statement (see Section 2.3), more rigorous environmental testing for specific design detail is expected when selected polymer materials do not meet such guidelines. For example, adhesives used for windshields have relatively low T_{gwet} but meet the requirements for such an application when subjected to extreme temperatures. Extensive field experience showing the suitability of a given adhesive applied in a particular application would supersede the need for additional tests. Regardless of meeting guidelines, any changes in material properties at temperatures above the MOT (for example, runway sun exposure) also need to be understood. An understanding of the intended manufacturing or repair facility's tooling concepts and process steps is also useful in material selections. Material suppliers often have data that can aid in selecting compatible materials for use in bonding.

Bond fabrication procedures should be well defined to perform trials that demonstrate compatibility between the substrates, adhesive, and processes. Some of the most important process steps relate to substrate storage, handling, and surface preparation. Reliable adhesive bonding depends on (1) a surface free of contamination, (2) a chemically active surface, and (3) dry surface.

The storage, handling, and surface preparation procedures needed to accomplish these characteristics will depend on the specific substrate and adhesive materials. There are distinct differences for composite and metal substrate materials. Sandwich core materials such as honeycomb and foam will also have unique process differences, depending on the base material type. Film adhesives have storage and handling requirements similar to pre-impregnated, uncured composite materials. Paste adhesives will likely have different components that require precise mixing before application.

Another important aspect of the bonding process is adhesive cure. The bonding surfaces must contact the adhesive with sufficient pressure and temperature to accomplish cure. The sequence, ramp rates, and dwell times for temperature and pressure application are defined in the cure cycle. Bond process tolerances should be explored and defined for resin mixing, surface preparation, and cure processing steps to document preliminary specifications during material compatibility trials. Such trials are carried out before proceeding with complete material and process qualifications. It is also wise to perform some bond process trials with representative structural geometry and tooling to ensure the bonding procedures can be taken beyond the laboratory scale. Material suppliers should help define bond process procedures.

Bonding materials and processes are qualified for use in structural applications. The overall goal of qualification testing is a basic characterization, which best represents the materials and processes in the application. As a result, specific specimen types and test conditions used in qualification will depend on the application. Most programs use some qualification tests to help set benchmarks in chemical, physical, process, and mechanical properties, which are used with other quality checks for subsequent material and process control. Enough unique batches of materials, independent bonding process trials and test repetitions are used to ensure a representative population for reliable benchmarks.

Substrate materials used in aircraft products are typically qualified before bond processes. Adhesive material qualification may also occur separate from bond process qualification. This is a common industry practice when an adhesive is going to be used with several different substrate materials because it is desirable to control the material with a set of properties that are not dependent on the specific bonding application. A separate bond process qualification is needed for each unique combination of materials because of the complex interface between substrate and adhesive, which depends on many variables (for example, material compatibility, surface preparation and cure kinetics). Sometimes, the adhesive and bond process qualification are combined for a specific set of materials.

The industry uses several different physical, chemical, and mechanical tests for adhesive material and bond process qualification. Physical and chemical tests may be used to control surface preparation, adhesive mixing, viscosity, and cure properties (for example, density, degree of cure, glass transition temperature). Industry uses lap shear stiffness and strength as the most common bonded joint mechanical tests for adhesive and bond process qualification. In addition to shear testing in an ambient environment, variables include extreme service temperature and moisture content conditions.

Although useful for material characterization and design, shear tests do not provide a reliable measure of long-term durability and environmental degradation associated with poor bonding processes. Some form of a peel test has proven more reliable for evaluating proper adhesion. This relates to the mechanical interlocking that occurs when adhesive penetrates the roughened surface of the substrate after preparation. The apparent bond static shear strength and stiffness may appear sufficient with mechanical interlocking, even if little or no chemical bond has formed during the process. Without chemical bonding, the so-called condition of a “weak bond” exists because mechanical interlocking is not adequate when the bonded joint is either loaded by peel forces or exposed to the environment over a long period of time, or both.

A wedge specimen that combines peel loads and extreme environmental conditions has proven to be a good accelerated lab test for detecting unacceptable metal bond processes, which degrade over time and lead to adhesion failures in service. Other specimen types that have been used to evaluate weak bonds for composites include double cantilever beam (DCB) and flatwise tension. Bonded sandwich specimens often use rolling drum peel or flatwise tension tests for similar assessments.

Adhesion failures, which indicate the lack of chemical bonding between substrate and adhesive materials, are considered an unacceptable failure mode in all mechanical test types. It is important to examine bonded joint failures to make an accurate assessment of whether adhesion failures are evident. In peel testing such as a metal bond wedge test, adhesion failure is the primary assessment. Material or bond process problems that lead to adhesion failures are solved before proceeding with qualification testing.

Material procurement specifications are used to control substrates, adhesives, and other materials important to the bonding process. This includes ancillary materials such as peel ply, which are known to affect the bond surface. The material specification will include requirements used for qualification and subsequent acceptance testing. A film adhesive specification has storage and handling requirements. A paste adhesive specification has such information for all components. The volatile content of adhesives is controlled for repeatable processing.

Users and suppliers should document agreements on what constitutes significant material changes, which may occur over time. Procedures should be available to judge whether a minor change can be validated by equivalency sampling tests or whether a complete requalification is needed for major changes.

Process specifications are needed to control adhesive bonding. Cleanliness and environmental controls are defined for shop areas used in bonding. Substrate storage and handling requirements are also documented in the specification or equivalent documents. Some key bond fabrication steps that use stringent process control include (1) surface preparation, (2) adhesive mixing and application, (3) bondline thickness tolerances, (4) cure cycle, and (5) post-bond inspection.

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 in successful applications. As for qualification tests, any process control test that reveals adhesion failures indicates a problem that needs to be resolved. The importance of in-process inspections and tests is magnified by the lack of reliable non-destructive inspections (NDI) to detect weak bonds or conditions that ultimately lead to adhesion failures in service. Although NDI methods (for example, ultrasonics) have limits in detecting weak bonds, they provide an important, final process control check of other defects found with bonded joints (for example, porosity, de-bonding and foreign material inclusions).

Documented procedures are needed to control process changes, which may be desired over time. If a change is minor, it may be validated through equivalency sampling tests. A complete bond process requalification is needed for major changes.

3.2 Design Development and Structural Substantiation

Most bonded joints and attachments are designed to transfer shear loads. Local peel forces are also present in a bond stress distribution, but structural details are typically designed to minimize such stress. The stress distribution and strength of a bonded joint or attachment relates to the substrate geometry (for example, thickness, taper angles), bondline thickness, bond overlap length and, if using composite substrates, laminate lay-up or fiber architecture. Residual stresses can be an important design consideration, depending on the directional differences in thermal expansion and stiffness of substrate materials.

Many bonded joints and attachments are designed to be fail-safe as related to small airplane regulations for composite damage tolerance. Alternate load paths are achieved by using fasteners or additional splices attached in a second bonding operation. Due to the mechanisms of bonded and bolted joints, the joint or attachment capability is designed assuming only the bond or bolts are transferring loads.

Analysis methods used by the industry to design bonded joints and attachments range from crude models to simple two-dimensional analyses to software-based tools, which include more refined structural definition. Crude models, which convert shear flow and other loads to an average shear stress, usually calculate bonded joint capability using very conservative design values. Despite the inherent conservatism, such an approach requires considerable testing of specific design detail in structural substantiation.

Both simple analyses and software-based tools predict local shear and peel stress distributions, which help design joint parameters for optimal performance. Some models include nonlinear elastic and plastic adhesive behavior for further joint optimization. Sufficient bond overlap length should be designed to ensure plastic deformation occurs without a risk to bond integrity or damage accumulation. In one guideline, the overlap length is designed to carry all loads by adhesive plastic deformation, with sufficient elastic trough away from the joint ends to provide creep resistance. Software models of adhesive joint geometry and load conditions allow further design refinement (for example, analysis of joggles).

An integrated product team (IPT) helps address important manufacturing, tooling, and maintenance considerations in bonded joint design. One related IPT goal is to design structural detail that can be reliably produced in the factory to meet the performance requirements. Similarly, the IPT needs to recognize the maintenance implications of future inspection and repair activities for bonded structural details.

Design criteria, analysis, and test data are needed for timely disposition of manufacturing defects and service damage, which are found in the factory and field, respectively. Sophisticated analysis methods to predict the effects of bond defects and damage scenarios continue to evolve; however, most applications to date depend on test data. This is particularly true when considering damage as complex as that caused by foreign object impact.

The design of bonded repairs uses many of the same procedures and tools applied to bonded joints and attachments. A typical bonded repair considers the patch geometry, scarf angle, and bondline thickness. Residual stresses resulting from a difference in the laminate lay-up, stiffness, and thermal expansion properties between the bonded patch and base part also need to be considered in repair design and analysis.

As discussed in PS-ACE100-2001-006, the overall approach applied for composite structural substantiation dictates design data development. The same philosophy applies for bonded structures. Some benefits are possible using a building block approach with refined analyses and test correlations for structural details, which range in size and assembly completeness (coupons, elements, subcomponents and components). Alternative approaches, based on crude analyses and a conservative demonstration of strength at the large scale, typically have more constraint. There is more freedom to expand beyond the specific structural details, damages, defects, and repairs addressed in large-scale tests if there is a more refined correlation between the analysis and tests within the building block approach.

Design data development includes characterization for minimum and maximum service temperatures, as well as the moisture content possible after years in service. A service damage threat assessment is also needed to define the full scope of structural tests and analyses. The materials, conditions, and processes used for repair in the factory and field often differ and need to be substantiated separately within the building block approach. Technicians involved in bonded joint testing should be trained to identify adhesion failures. Any adhesion failures noted through the course of building block testing are considered unacceptable.

The long-term durability of bonded joints also needs to be addressed. As discussed in Section 3.1, bond process qualifications usually initiate these efforts using accelerated test procedures that force an assessment of the chemical bonding. The long-term environmental exposure to temperature, moisture and other fluids found in service is also characterized by testing, as discussed in Section 3.1. Element and subcomponent tests provide further proof of acceptable bonding processes applied at larger structural scales.

Final substantiation of static strength, fatigue, and damage tolerance relies on large-scale test components manufactured using production processes. Building block analyses and tests can be used to determine most of the effects of structural details, damage, defects and repair. However, large-scale tests are still needed for final proof of the design and manufacturing characteristics of configured structures, which include bonded joints, cutouts, damage, repairs and combined loads. This includes validation of load paths and a final strength assessment. For example, integrally bonded airframes often have secondary load paths and complex failure modes that are difficult to predict.

Moisture and temperature property degradation is often handled in large-scale tests using overload factors derived from smaller scale tests. One issue that is difficult to directly address in large-scale tests is the completed cure of the adhesive and the availability of related peak moisture and temperature-dependent properties at the structural level. In addition to the process controls used to ensure sufficient temperature conditions for the required cure cycle during fabrication, some laboratory testing of samples cut from the bonded structure can provide the necessary substantiation of manufacturing processes.

3.3 Manufacturing Implementation

When implementing new bonding facilities and fabrication processes, manufacturing trials are needed to develop an understanding of structural details that can be reliably produced. Scaling issues, which directly relate to structural details, are likely for several bond process steps including surface preparation, adhesive application, and cure control. Tooling used for bond assembly and cure will depend on mating part geometry, cured tolerance controls, and other factors that relate to design details. An iterative process of defining structural details and performing manufacturing trials, and testing for performance has proven successful for new design development in the past. Such efforts become more efficient as a manufacturer gains experience in bonding applications.

Special facilities and procedures are needed to manage and control materials and key bonding process steps. The associated issues relate to cleanliness, environmental conditions, storage, material life, processing records, staff training, and maintenance. Material control discussed in Section 3.1 as pertaining to procurement specifications is applied to ensure batch-to-batch consistency. Factory procedures and records manage the storage conditions, shelf-life, out-life and handling of all uncured materials to ensure they meet the associated specification requirements. Cold storage conditions and handling procedures (for example, time required in the ambient environment before unpacking for use to avoid condensation) are needed for some types of adhesives. The environmental storage conditions of some substrate materials may also need to be controlled (substrate materials and bonding processes affected by pre-bond moisture). Facilities and procedures for control of the bond assembly environment, equipment, tooling and factory personnel are needed to manage all sources of contamination. Expendable materials used in bonding processes are also controlled to manage sources of contamination and avoid changes in bond process steps. For example, chemicals and blast media used for different surface preparation techniques are controlled, discarded, and replaced as needed to maintain process standards. Factory maintenance of facilities, equipment, and tooling is used to ensure the cleanliness and material and process controls needed for repeatable production of bonded structure.

Many experts consider surface preparation to be the most important process step for structural bonding. There are distinct differences in the surface preparation techniques used for metal and composite substrates. Phosphoric acid anodizing and grit-blast/silane processes are examples of surface preparation techniques that have worked for aluminum substrates. Sanding, media blasting, and peel ply surface preparation techniques have been successfully used for composite bonding, depending on the specific substrate and adhesive combinations. Bonded sandwich construction, which uses honeycomb or foam core material (composite or metal), requires specific procedures for core surface control applied to achieve successful bonding. The use of some solvents on honeycomb core surfaces can cause subsequent bonding problems. The surface preparation procedures used for wood sandwich core materials (e.g., balsa) typically include abrasion.

Manufacturing scaling issues for a particular bonded structure need to be considered when selecting a surface preparation for bond process qualification. The substrate surface morphology and chemistry, which are created by a qualified surface preparation process, are not changed in production implementation. Since specific bonded part geometries are often more complex than specimens used for qualification, additional processing challenges exist. Some production process controls used to monitor surface preparation include visual checks, polarized light checks, water break tests, chemical analysis, and mechanical tests using samples from bonded witness panels. Once a surface is prepared, some processes rely on time constraints during bond assembly, requiring surface preparation to be repeated if the bonding operation does not occur within the specified time.

There are geometric, fit-up and other timing issues to consider in bond assembly. Cured dimensional tolerances and warpage are controlled for mating parts. Since the bondline thickness affects the local bond stress distribution and strength, it is also monitored using process checks. Assembly jigs and procedures can provide pre-bond gap assessment. Processing aids (for example, verafilm) are used to assess the tight tolerances needed for some bonding processes. Handling requirements and procedures exist to control the film adhesive lay-up process. The mixing and application of paste adhesive require additional processing steps and controls. The mixing ratios of paste adhesive constituents and filler content are controlled and monitored. Tight controls are also applied to determine the completeness of the mixing process. Depending on the type of paste adhesive used, bond assembly time constraints from adhesive mix to mated surface contact are implemented. The minimum bondline thickness can be controlled using a number of different spacer types (for example, scrim cloth, glass beads and micro balloons). The tolerances of assembly jigs are monitored and maintained over time.

The cure of bonded structures is controlled to ensure that the adhesive properly wets the substrate surfaces and dwells at temperatures needed to fully develop the properties for intended applications, without overheating. As discussed previously, the scaling issues associated with bonding large-scale airframe structures are complex. Heat transfer, bond surface contact pressure, and adhesive characteristics during different stages of the cure cycle all combine to affect the final state of the bond at local points throughout the structure. Manufacturing trials are typically needed for new combinations of parts, tooling, and equipment. Tolerances are established and in-process controls are implemented to locally manage the bond cure cycle and avoid overheating. Cure tooling and the equipment used to apply temperature to structures during bonding is controlled and maintained. Procedures used for in-process monitoring are validated and regularly calibrated.

Manufacturing quality management is important to many aspects of bonding. A combination of strict in-process controls and post-bond inspections is used. The NDI of bonded structure provides necessary, but not sufficient, evidence that proper bonding has been achieved. Current NDI methods, such as ultrasonic methods, can locate areas of de-bonding, porosity and foreign inclusions (for example, peel ply or backing paper left in the bond line) but are unable to reliably detect defective bonds resulting from contamination or incorrect materials or processing. The latter condition is best controlled through in-process checks. In-process quality controls are usually applied to surface preparation, adhesive mixing, bond assembly and cure. Witness panel tests consider the combined affect of these process steps but for a simplified geometry. As a result, other quality measures and controls provide supplemental checks on the real structure.

Another area of manufacturing and design integration that is needed moving into production is the disposition of processing flaws. As discussed previously, design data development and structural substantiation support this technical issue.

Factory technicians and quality personnel involved in various bond process steps are trained in specific areas of responsibility. Adhesion failures and the associated cause are properly identified and corrected. Records are kept on material usage, process steps, and quality checks applied to each bonded structure. Factory or service problems associated with weak bonds or de-bonding that cannot be traced to specific material batches or manufacturing mistakes indicate unreliable bonding processes.

3.4 Repair Implementation

Many of the technical issues, which were discussed in the previous three subsections, are important to bonded repair implementation. This subsection will briefly review the issues and emphasize the unique aspects related to bonded repair. An assessment of the full extent of damage that requires a bonded repair is the starting point for current discussions. In most cases, this may require NDI of the damaged area.

As discussed in Section 3.2, bonded repairs have many of the same design considerations as bonded joints and attachments. Adhesive and patch materials selected for bonded repairs are substantiated for specific design and process details. Factory and field repairs using different materials, designs, or processes require separate substantiation.

A building block approach that includes approved data from analysis and test correlation for structural substantiation of bonded repairs has many advantages. Such an approach provides both a strong basis for maintenance documents and additional freedom to develop more repairs for damage not previously covered, without returning to large-scale tests. Benefits are also possible by validating analysis tools that use the actual repair geometry and load transfer characteristics. Maintenance documents with details on approved inspection, damage disposition, and repair procedures save time. Allowable damage or defects and bonded repair limits should also be documented. Repair designs that use bonding and fasteners consider the capability of each joining method separately (fasteners will not be effective until bond failure occurs).

Materials and processes used for bonded repair are qualified. Section 3.1 discusses the qualifications and associated material acceptance and process controls used for bonding. Section 3.3 expands discussions on the management and control of materials and key bonding process steps as related to manufacturing implementation. The critical technical issues remain the same for repair implementation, but facility requirements are typically posed at a smaller scale.

Specification requirements for storage conditions, shelf-life, out-life, and handling of materials are managed by using repair shop procedures and records. Procedures for control of the bonded repair environment, equipment, tooling, and shop personnel are needed to manage all sources of contamination. Any expendable material used in bonding processes is also controlled to manage sources of contamination and avoid changes in the bond process steps. Shop facilities, equipment, and tooling are maintained to ensure the cleanliness and the material and process controls needed to fabricate acceptable bonded repairs.

Important process steps (for example, damage removal, surface preparation, adhesive application, and cure) will depend on issues related to the specific damage and structural details that require bonded repair. Additional issues become important when structure is such that the bonded repair must be performed on-airplane. Maintenance documents need to take part-specific issues into account. Damage removal for composite substrates often requires the creation of a surface with a scarf angle, which is held within specified tolerances. Damaged core removal and replacement, or filling with a suitable polymeric material, is common for sandwich construction. Bond surface preparation is still one of the most important process steps.

The field state of substrate materials will likely require more attention than new parts stored in a controlled factory environment. Water, oil, and hydraulic fluids, which may be present, need to be removed in the area of the structural repair to avoid contamination and curing problems. Moisture or other fluids that absorb into composite or core materials (honeycomb or foam) over time in the field may also cause bonding problems at cure temperatures. Field procedures to remove sources of contamination, moisture, and other fluids need to be defined and documented.

Cure of bonded repairs in the field requires special attention, including methods of applying heat and pressure (for example, heat blankets, vacuum bagging and control devices). Depending on the method of applying heat, structural details, adjacent systems, and whether or not the repair is performed on the airplane, the heat transfer to cure a bonded repair may be very complex. Structures on an airplane have different framing elements, systems, and entrapped spaces below the outer surface that alter heat flow versus that of the bonded repair to a part removed from the airplane and cured in factory or shop equipment (for example, autoclaves and ovens). In-process measures and controls are needed to ensure proper heat-up rate and dwell at the cure temperature over the entire bonded surface of the repair.

Overheating the repair or adjacent structures to cause structural damage or degradation is avoided. Proper placement of thermocouples or other thermal measuring devices to monitor the lowest and highest temperatures during cure of bonded repairs is important to process control. Unique heater configurations and repair scenarios for specific structures benefit from pre-bond heating trials to ensure proper placement of the devices used for thermal control. If it is found that a bonded repair cannot be performed properly on-airplane, the manufacturer should be contacted for alternate methods (for example, approved bolted repair).

Quality management is important to many aspects of bonded repair. Therefore, some combination of in-process controls and post-bond inspections is used. As is the case for structural bonding in a factory, NDI alone provides necessary, but not sufficient, evidence that proper bonding has been achieved. Other repair quality controls are usually applied to surface preparation, adhesive mixing, bond assembly, and cure to complement NDI.

Another area of bond process and design integration that occurs is the disposition of repair mistakes and processing flaws. As discussed previously, design data development and structural substantiation support this technical issue.

Technicians and inspectors involved in various bonded repair process steps are trained in specific areas of responsibility, including the proper use of equipment. Records are kept on material usage, process steps, and quality checks applied to each bonded repair. Adhesion failures and the associated cause are properly identified and corrected. Such problems that cannot be traced to specific material batches or a repair process mistake indicate unreliable bonding processes. Bonding problems are reported to engineering staff.

3.5 Service Experience

Service experience of bonded structures and repairs provide the final proof of a reliable bonding process that has been properly executed. Discovery of bond adhesion failures in service justify immediate directed inspections and repair. Thorough production or repair records are important to tracing the probable cause of such a problem.

Some experts believe that service monitoring of bonded structures or repairs, including selected NDI, and teardown inspections for retired aircraft, provides data to correlate accelerated test results from qualification and in-process control with real-time service exposure. The FAA plans to continue to work with industry in this area of life assessment.

4.0 Certification Considerations

This section covers certification considerations for the type design, production, and maintenance of aircraft products that use bonding in joints, attachments and repairs. Section 3.2 emphasizes the importance of an IPT approach for design and substantiation of bonded structures. This approach ensures the bonded structural details are producible and subjected to quality control procedures. This also ensures key characteristics of the substantiated design are met, and accessibility of bonded structure for inspection or other maintenance functions is incorporated into the design. Efforts in structural substantiation, which occur during certification of the type design, typically have a bearing on subsequent production and maintenance. Either design data or validated analyses, or both, are needed to disposition manufacturing defects and service damage. Rework and repair procedures and repair designs need to be substantiated for both factory and field implementation.

4.1 Design and Construction

Drawings and specifications are needed to define the product type design. This includes information on the dimensions, materials, and processes necessary to define the structural strength of the product. Design and process details known to affect the performance of bonded structures are included in the type design data and controlled in production. As stated in § 23.601, tests are used to demonstrate the suitability of each questionable design detail or part having an important bearing on safety in operations.

All new materials and fabrication methods require testing to qualify their use in design and construction of aircraft structure. This includes taking into account the effects of environmental conditions, such as temperature and humidity. Use qualification test results to help derive material and process controls. Material procurement specifications control adhesives, substrates, and ancillary materials used for bonding processes. Each specific combination of adhesive, substrate materials, and bond process procedures is qualified. Material qualification of an adhesive used with different substrates and bonding processes may be established separately to support subsequent material control; however, each unique bond process still requires qualification and supporting data.

Fabrication methods are required to “produce consistently sound structure” per § 23.605. Use of the word "sound" in the context of bonded structure means structure with adequate strength and durability. Section 3.1 has some discussion on strength and durability tests for bonded joints. Accelerated test methods that have been successfully applied for the latter use cleavage forces to expose the bonded surfaces to extreme environmental conditions. Such tests help detect a weak interface, which is associated with poor bonding processes. Any significant amounts of adhesion failures noted in qualification tests are an indication of either incompatible materials or inadequate bonding processes, or both. In § 23.605, there is also a specific reference to fabrication methods such as “gluing, spot welding, or heat-treating” as processes that require an approved process specification. Adhesive bonding is such a process.

Relationships with material and process controls help establish the minimum number of batches, process runs, and test repetitions needed in generating qualification data. If the qualification tests performed were insufficient to properly characterize bonding materials and processes, subsequent controls will be difficult to meet.

As outlined in PS-ACE100-2002-006, experience has shown that material qualification is based on a minimum of two process runs and three replicates per run for each of three material batches. This approach remains feasible for adhesive material qualification or a coupled adhesive material and bond process qualification. The recommendation for a separate bond process qualification is based on a minimum of six bond process runs, each with a unique batch combination of qualified adhesive and substrate materials. Material strength properties and design values derived from qualification or other tests will not contain any data with significant evidence of adhesion failure. Equivalency testing is used to validate minor changes in bond materials or processes. A major change requires a complete requalification.

4.2 Structural Substantiation

Policy Statement PS-ACE100-2001-006, for static strength substantiation of composite airplane structure, also applies to bonded structures. A key point from this policy is the need for large-scale tests to validate new structural design and manufacturing construction per §§ 23.305 and 23.307. This policy also covers other aspects of static strength substantiation including building block approach, structural analysis, environmental effects, manufacturing anomalies, impact damage, and overload test factors. In general, building block analyses and tests can be used to reduce the amount of large-scale testing and eliminate some overload factors used in final proof of structure for new designs. Such an approach may also be applied for final proof of structure in lieu of large-scale tests only if the design and manufacturing details conform to those which experience has shown the method to be reliable (for example, derivative aircraft).

Some additional guidance on the static strength substantiation of bonded structure relates to specific design detail, sizing approaches, and test considerations. Any adhesion failures noted during building block or final proof of structure testing are identified and linked to a specific cause (for example, manufacturing mistake) and corrected for subsequent certification. The use of coupons to derive overload factors to cover all aspects of environmental effects and an average shear stress analysis should be viewed with caution. For example, such practice often does not cover real-time degradation mechanisms such as the poor creep resistance of bonded joints with insufficient overlap length or the effects of secondary load paths that may exist in real structure. Data needed to substantiate a simple sizing approach includes sufficient testing with enough structural detail to account for foreseeable property variability, while ensuring the structure meets realistic environmental and loading conditions.

Large-scale tests are also needed to validate the fatigue and damage tolerance of bonded structure with new design and manufacturing construction, per § 23.573. Building block analyses and tests provide support similar to static strength substantiation. Defect and damage threat assessments provide the starting point. Static strength and fatigue evaluations include manufacturing anomalies and accidental damage that may not be detected by factory quality control or field inspection methods. Damage tolerance evaluations include accidental or environmental damages that are detectable in the field, ranging from small sizes that require directed inspection to more severe damage that would be readily detected within a few flights. Within the scope of static strength, fatigue and damage tolerance rules, it is intended that circumstances leading to lost ultimate load capability should be rare.

Part 23 regulations have language specific to bonded structure in § 23.573(a)(5), which has three options to substantiate limit load capability (see Section 2.1 for a quote). These options do not supersede the need for a well-qualified bonding process and rigorous quality controls for bonded structures. For example, 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 (for example, insufficient cure or contamination). Static proof tests to limit load, which are posed as the second option, may not catch weak bonds that require time and environmental exposure to degrade the strength of a bonded joint. Finally, the third option is open for future advancement and validation of NDI technology to detect weak bonds, which degrade over time and lead to adhesion failures. As discussed in Section 3, such technology has not been reliably demonstrated at a production scale to date.

It is impractical to directly evaluate the long-term durability of bonded structures, which includes real-time environmental exposure, in large-scale tests before certification. As discussed in Sections 3.1 and 3.2, aggressive environments and extreme loading (for example, cleavage forces) are used in smaller scale tests to expose bonded interfaces to conditions, which are known to accelerate degradation mechanisms for weak or contaminated bonds. Although this approach helps ensure good bonding processes, the long-term durability of bonded production aircraft structure is validated by service experience. As a result, close ties between the service and production departments of a manufacturer are essential.

4.3 Production

Quality management is essential for production of bonded structure. The facilities control environment and cleanliness of bonding processes to a level validated by qualification and proof of structure testing. Adhesives and substrate materials are controlled to specification requirements that are consistent with material and bond process qualifications. This includes requirements for storage, handling, and material characteristics or process parameters needed to achieve consistent chemical, physical, and mechanical properties. Expendable materials used in bonding processes are also controlled and disposed per requirements to insure the integrity of bonded structure. Document plans for regular maintenance of production facilities.

Process steps, equipment, and tooling crucial to achieving structural bond integrity are fully defined and controlled within tolerances given in specifications or equivalent documents. The production tolerances meet standards validated in qualification, design data development, and proof of structure tests. Some key bonding process steps requiring such control include: (1) surface preparation, (2) mating part dimensional tolerance control, (3) adhesive mixing and application, (4) bondline thickness, and (5) adhesive cure. Document plans for regular maintenance of production equipment and tooling.

Production certificate holders show that a quality control system has been established and maintained for bonded structures. As discussed in Section 4.1, methods of fabrication reliably produce structure with adequate strength and durability. Process control and production records document the key characteristics (KC), key process parameters (KPP), or equivalent data, which indicate the bonding processes were properly applied. Changes in the quality control system are subject to review by the Administrator.

A disposition process is needed for all manufacturing defects and nonconformities detected by the quality control system. Either design data or analyses, or both, validated by previous tests are used for acceptance, rework or repair. Any adhesion failures discovered during production require immediate actions to isolate the problem and determine the cause.

4.4 Continued Airworthiness

Bonded structures and repairs need to meet continued airworthiness requirements. Maintenance inspection and repair work is needed for damage due to accidental events (for example, foreign object impact), environmental effects or other causes. The initial detection of damage in composite or metal bonded structures is followed by more extensive inspection (for example, ultrasonic methods) to determine the full extent of damage requiring repair.

Inspection and repair process steps documented in maintenance manuals that are based on approved data (procedures validated by qualification and structural substantiation) provide a number of advantages. If damage is beyond the scope of that previously approved, the manufacturer or other approving authority will be involved in the disposition, and additional data may be required for substantiation. Any de-bonding, which includes significant adhesion failures, found in service are reported to the manufacturer. Such findings require immediate action to identify and correct the cause of de-bonding (for example, manufacturing error). Records are kept for maintenance activities, including repair, inspection, and rework.

Quality management is essential for bonded repairs to airframe structures, which are performed in a shop or on the aircraft. The environment and cleanliness of repair bonding processes are controlled to a level validated by qualification and proof of structure testing. Adhesive and substrate repair materials are qualified and controlled to approved specifications. This includes requirements for storage, handling, and material characteristics or process parameters needed to achieve consistent chemical, physical, and mechanical properties. Expendable materials used in bonding processes are also controlled and disposed per requirements that ensure the integrity of a bonded repair. Document plans for regular maintenance of repair shop facilities, equipment, and tooling.

The bonded repair of airframe structures in service follows the same basic principles as bonding performed in the factory. However, technical issues related to the damaged condition of the structure need to be addressed, and the associated additional process steps are documented in approved repair procedures. The procedures also recognize and address the field difficulties of applying process steps to a specific repair.

Repair starts with a determination of the full extent of structural damage, including necessary inspections, and an engineering disposition. Damaged material, paint, and other surface coatings are removed per approved processes.

Removal of aviation fluids, cleaning, and drying of the structure also follows approved procedures. Process steps for surface preparation, adhesive mixing, application of repair materials, and bond cure are defined, applicable, and complete for the specific repair to be performed. The necessary equipment, tooling, and ancillary materials needed to perform the bonded repair are available.

Perform and record process control data and quality inspections, which are defined in approved procedures for bonded repair. Quality controls address the field difficulties of preparing a chemically active bond surface and applying the proper heat-up rate, cure temperatures, and dwell times throughout the repair. Records for a successful bonded repair indicate the process was correctly performed to produce sound structure with a high degree of reliability.

A disposition process is needed for nonconformities (for example, insufficient cure temperature, overheating) and defects (for example, porosity, de-bonding) found by inspection. Procedures based on approved data are used for acceptance and rework.

4.5 Other Elements

Industry-accepted engineering databases, specifications, guidelines, and test standards continue to evolve with the help of organizations such as MIL-HDBK-17, SAE AMS-P17, SAE CACRC, and ASTM. Use of such information is encouraged in the development, certification, production, and maintenance of bonded structures. The specific application of standards to a particular aircraft product is approved in the substantiation process. The use of some data requires a demonstration of material and process control. For example, an equivalency test sampling process is used for new users of material data that depend on manufacturer processing (see ACE-100 Policy Statement "PS-ACE100-2002-006").

The importance of communication and coordinated work between design, production, and service groups involved in bonding has been covered in this document. Such an interface is essential when a potential bonding problem has direct implications to safety and continued airworthiness. Adhesion failures found during qualification or structural substantiation indicate either incompatible materials or unacceptable bond processes, or both. Adhesion failures found in production require immediate actions to identify the specific cause and isolate all affected parts and assemblies for disposition. Adhesion failures discovered in service require immediate actions to determine the cause, to isolate the affected aircraft, and to conduct directed inspection and repair. Such cases are immediately reported to regulatory authorities and, depending on the suspected severity of the bonding problem, the regulatory authority may ground the aircraft.

Engineers, technicians, and inspectors involved in related design, production, and maintenance activities need a basic understanding of the critical technical issues and processing procedures used for bonded structures and repairs. Factory work force training is needed to ensure proper execution of specific bonded structure processing steps and quality inspections. Maintenance work force training is needed to ensure proper execution of specific bonded repair processing steps and quality inspections.

5.0 Summary

Under CS&CI, the FAA has worked with industry, government agencies, and academia in support of focused research for the bonded structures. In 2004, the FAA conducted an industry survey and two bonded structure workshops. The objective is to benchmark industry practices and collect information on the critical safety issues and certification considerations for bonded aircraft structures and repairs.

Building on the data collected through the survey and the workshops, the Small Airplane Directorate (ACE-100) developed this policy statement to provide guidance from regulatory perspectives. This policy statement applies to 14 CFR part 23 airplanes.

The bonded structures may include composite-to-composite, composite-to-metal, and metal-to-metal. These structural bonding applications have been used for both manufacturing and maintenance (repair) operations.

Considering continued operational safety, the scope of this policy statement covers (1) material and process qualification and control, (2) design development and structural substantiation, (3) manufacturing implementation, and (4) maintenance implementation.

6.0 Future Efforts and Standardization

This policy statement serves as initial guidance for certifying bonded structures for 14 CFR part 23 airplanes. Efforts in bonded structures will continue with plans for future updates to the policy and guidance.

The related research on critical bonding issues will remain active. The FAA will also continue to support industry and working groups in developing engineering standards for structural bonding.

Effect of Policy

The general policy stated in this document does not constitute a new regulation or create what the courts refer to as a "binding norm." The office that implements policy should follow this policy when applicable to the specific project. Whenever an applicant's proposed method of compliance is outside this established policy, it must be coordinated with the policy issuing office, for example, through the issue paper process or equivalent. Similarly, if the implementing office becomes aware of reasons that an applicant's proposal that meets this policy should not be approved, the office must coordinate its response with the Small Airplane Directorate.

Applicants should expect that the certificating officials would consider this information when making findings of compliance relevant to new certificate actions. Also, as with all advisory material, this policy statement identifies one means, but not the only means, of compliance.

If you have any questions or comments, please contact Mr. Lester Cheng, Regulations and Policy Branch, at 316-946-4111.

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