Qualified Bonded Systems Approach to Certified Bonded Structure

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ABSTRACT

To ensure the reliability of structural bonds on Boeing Aircraft products both during manufacture and in-service, the design and execution of any structural bonded joint must be demonstrated by test to produce a strong and durable bond along with consideration of the full processing windows allowed by the governing specifications. This standard is required to satisfy FAR 25.605 and to comply with FAA guidance in AC20-107B and the US Department of Defense's JSSG-2006. Boeing has defined a "Bonded System" as consisting of the adherend material, surface preparation method, adhesive, and bonding process conditions used. Each component of the Bonded System must be thoughtfully selected and rigorously evaluated for any variables that could affect bondline quality. Any proposed changes in a Qualified Bonded System made during manufacturing or the life of the production system, must be evaluated by multiple methods that interrogate adhesion, consistent bondline performance, and durability across the spectrum of variables. Boeing has taken this approach on large scale production implementation of technologies that greatly improve the reliability of the bonded system process. For example, automated methods, such as atmospheric plasma surface preparation methods that produce a known, reproducible surface have been implemented. Additionally, next generation in-line bond process monitoring tools and bond strength characterization methods are being developed to provide an automated record of critical bond process conditions and reduce variability in bonded joint performance. These Qualified Bonded System approaches will be outlined in this talk.

1.0 BACKGROUND

Bonded joints in aerospace structures have the potential for significant performance and service advantages over traditionally fastened structure. In addition to greatly reduced part count, the reduction in the number and size of fasteners avoids the secondary design requirements driven by these features, allowing improved joint geometry in the form of reduced component thickness and weight and more efficient load paths [1].

Similarly, the reduction in the number of fastener holes and the distributed nature of bonded load transfer eliminate many of the stress concentrations which drive fatigue and related progressive deterioration. While the benefits of bonding apply to both metallic and nonmetallic materials, bonding has proven particularly attractive for fiber reinforced plastic composites because of complications with bolted attachment of these materials. Bonding has enjoyed widespread use on secondary structure, but has limited examples in primary structure due to stringent design requirements and relatively recent advances in manufacturing capabilities. In recent years, major composite structure using bonding as the primary load path has been incorporated into a number of military and civilian aircraft. In a limited number of cases, these structures rely solely on the adhesive bond for structural integrity without the presence of mechanical fasteners for damage arrestment or redundancy.

While manufacturers have successfully certified a number of bonded primary elements, the certification of these structures has been conducted as a nonstandard process unique to each feature. The evolution of governing regulations and a desire to more efficiently conduct the certification process suggest that a systematic review of fundamental principles and issues surrounding bonding certification would be useful.

To ensure the reliability of bonded joints in critical applications, a comprehensive and coordinated approach is applied to the design and all aspects of the Qualified Bonded System. Areas of focus include the development of certification criteria and requirements, robust materials and processes, effective process monitoring and inspection, and development of efficient design, analysis, and substantiation tools.

1.1 Regulations

The certification of aircraft structure is dependent on regulatory agency approval – the Federal Aviation Administration (FAA) for civilian aircraft and the Department of Defense (DoD) for military aircraft. Certification is obtained through a process of substantiation and documentation which demonstrates that a design (type certification), its manufacture (production certification), and the aircraft itself (airworthiness certification) satisfy all relevant legal regulations. These regulatory requirements represent a minimum standard for the qualities and performance of the aircraft, and are distinct from the design requirement and objectives defined by the manufacturer based on their own criteria for risk and performance.

FAA requirements give oversight to ensure the reliability of structural bonds on commercial aircraft both during manufacture and in-service. The design and execution of any structural bonded joint must be demonstrated by test to produce a strong and durable bond when considering the full processing windows allowed by the governing specifications. This standard is required to satisfy FAR 25.605 [2] and to comply with FAA guidance in AC20-107B [2]. Specifically, this standard is intended to ensure that there is test substantiation and appropriate controls for a process-sensitive fabrication method as required by FAR 25.605. In line with the guidance in AC20-107B, the bonded joint is considered as an interdependent system of materials and processes, which must produce consistent and reliable joints within the parameters allowed in that definition. Furthermore, FAA requires that all critical structure have a repair size limit no larger than a size that allows limit load strength to be achieved with the repair failed. This requirement is needed to ensure limit load capability in the event of bonded repair failures such as “weak bonds” [3].

Guidance from the military aircraft sector includes the DoD’s Joint Service Specification Guide (JSSG-2006) [4], which is a broad manuscript describing the overall specification guide for all of its aircraft structures. This document provides that: bonded structures shall be free of disbonds and be capable of sustaining residual strength loads without a safety-of-flight failure with a complete bondline failure or disbond; a system to be used to minimize the probability of occurrence of low-strength bonds; adequate process controls to be used during bond assembly fabrication; and the establishment of non-destructive test methods to minimize the probability of bond failure.

In general, these regulations are written without reference to particular manufacturing methods or structural configurations, and the text of the regulations themselves provides minimal insight into the appropriate steps to certify an adhesively bonded structure.

1.2 Design Requirements and Objectives

An equally important part framework for bonded structure compliance are internal company Design Requirements and Objectives (DR&Os). DR&Os provide definition and requirements specific to an aircraft architecture, design, and components to maintain the integrity of the product in alignment with particular program needs to ensure that the product meets customer, company, and regulatory requirements. These documents establish a basis for implementing practices and procedures to meet these requirements in an effective, predictable, and repeatable manner.

1.3 Evolution of Bonding in the Fleet

Early metallic aircraft designs consisted of aluminum skins, doublers, and honeycomb cores and were typically bonded with epoxy adhesives. Over time, bonding technology applications grew to include control surfaces, doors, body skins, fairings, and similar structures [5]. As bonded designs became more mainstream, the wider range of in-service conditions and stresses created a need for new adhesive chemistries, including toughened epoxy systems and higher temperature polymers, such as bismaleimides and polyimides. Adhesive bonded designs also gave unique opportunities for more complicated applications such as rotor blades and wing-to-body joins. Throughout this history, the industry has suffered from periodic bond quality failures.

While the industry's experience with adhesive bonding of load-carrying structure has generally been good, there have been periodic examples of failures throughout the fleet, Figure 1-1. During the early 1960s, lap splice and tear straps were introduced into aircraft design and were bonded using a room temperature curing adhesive in combination with riveted structure. Over time, these joints experienced issues with corrosion and disbonding. These issues and other experiences through the subsequent decades led to the development of corrosion inhibiting bond primers, better surface preparation techniques, and adhesives that were less sensitive to moisture ingression, as well as improved designs that removed this cold bonding from the lap splice areas of aircraft models [6]. Targeted work, such as the Air Force Primary Adhesively Bonded Structures (PABST) program [7] served to characterize the methodology and best practices for the use of reliable bonded joints.

Figure 1-1. Examples of failed aluminum bond structure; (left) aileron corroded aluminum honeycomb sandwich; (right) trailing edge flap skin disbond due to poor surface preparation.

Structural bonding of titanium has enabled the development of new hybrid high performance structures, making them lighter, simpler, and easier to maintain while increasing airplane performance and efficiency. For example, the F/A-18 wing root structure consists of a titanium alloy fuselage attachment fitting bonded to the Carbon Fiber Reinforced Plastic (CFRP) wing structure through a step lap joint configuration and is considered one of the most critical primary bonded structures in the flying worldwide aircraft fleet. Residual strength static testing conducted on specimens extracted from decommissioned F/A-18 wings by the National Institute for Aviation Research (NIAR), showed that the sustainable load carrying capacity of the aged bonded joints was comparable to pristine, unexposed structure [8]. This work has demonstrated the structural reliability of this bonded joint for over four decades of fleet usage.

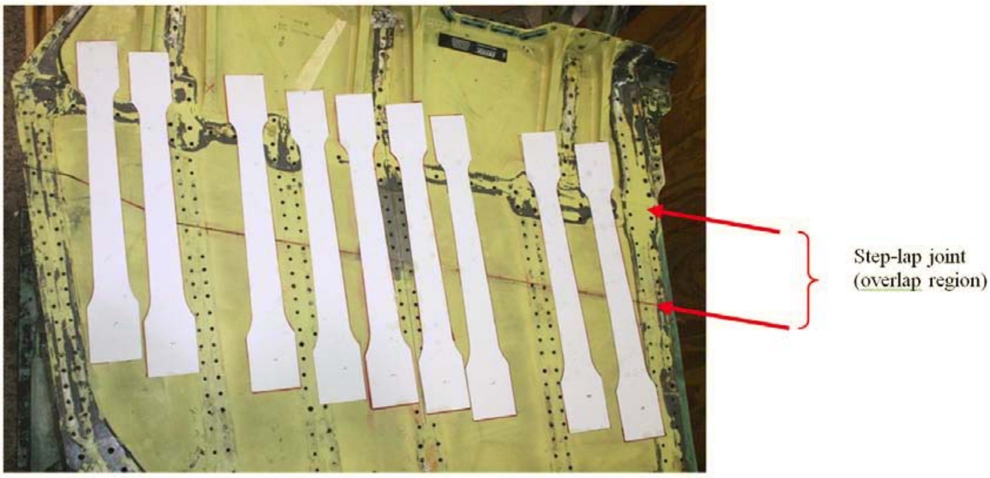

Figure 1-2. Durability and residual strength assessments of specimens extracted from decommissioned FA-18 A/D wing-root step lap Ti-CFRP bonded joints [8]

While the emergence of structural composites has enabled the industry to move away from the corrosion and moisture-induced debonding issues associated with metal bonded structures, opportunities existed for selection and deployment of materials with non-optimized performance. Selection of bonded systems tended to be based on an incomplete understanding of the fundamentals of the composite interface and the use of empirically-produced tools and data. The use of incompatible peel ply surface treatments or peel ply materials containing release agents to make them easier to remove the peel ply from the bonding surface, yielded a range of performance from moderate strength to low strength or kissing bonds. In some cases, release agent was transferred to the surface; in other cases, the peel ply chemistry itself, such as some uses of nylon peel ply materials, left a chemistry on the surface that was not optimally amenable to strong reliable bonds, as was seen in key findings from Hart-Smith, et al. [9]. Polyester-based peel plies also required caution to ensure that these materials were not degraded by the cure cycle or prepreg moisture conditions and that they were compatible with the chosen bonded system.

Experience gained during the development and application of all bonded structures has clearly demonstrated the need to consider the combination of elements that combine to produce a bond as a unified system. As described above, surface preparation methods which are effective for some materials may not produce reliable bonds with even closely related substrates, and seemingly minor changes within a qualified product or established process can significantly affect the strength of the resultant bond. At the same time, our level of fundamental understanding of the bond processes have not been sufficient to reliably predict the impact of alternative bondline components or processes. As a consequence, establishing and maintaining a reliable bond process requires close definition of the allowed materials and processes, combined with extensive experimental validation of the potential process variations at the corners of that definition.

2.0 QUALIFIED BONDED SYSTEMS CONCEPT

The recognition of the need for this level of control has led to the systems-level concept of a Qualified Bonded System (QBS), intended to represent a combination of materials and processes which have been demonstrated to produce a reliable structural bond. A Qualified Bonded System consists of all of the materials used in the bonded joint and the processes used to create the bonded joint, Figure 2-1. To be considered a QBS, all components and processes that make up the bonding process must be controlled to the level of qualified materials and process specification documents, and test data must exist to demonstrate that all variations allowed within those definitions will produce a bond with acceptable quantitative and qualitative performance.

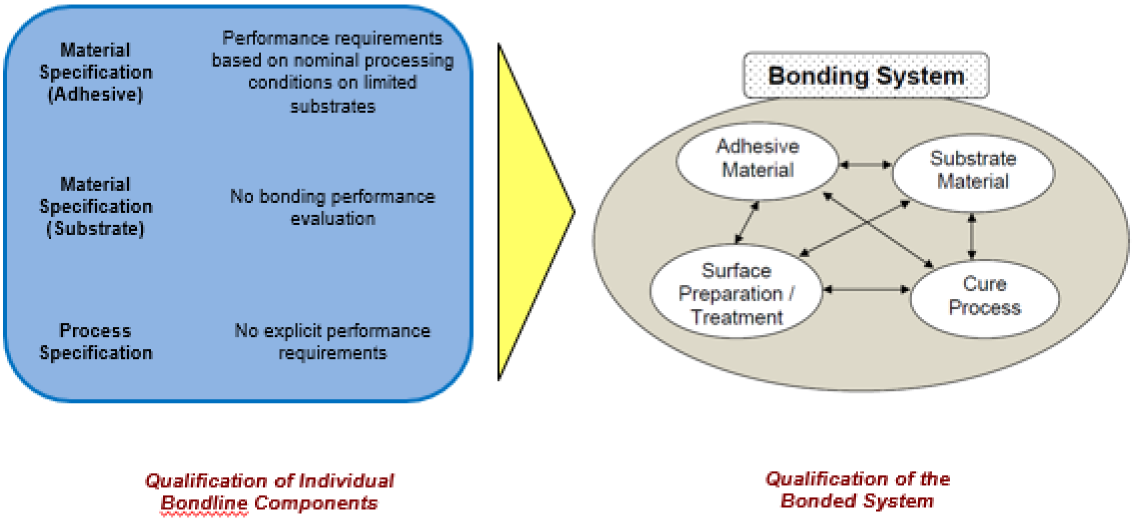

Figure 2-1. Moving from qualification of individual components to qualification of the bonded system to achieve robust and reliable performance.

Using the QBS approach, each component of the bonded system and the interactions between components must be validated to demonstrate that a stable and repeatable system has been achieved. In order to do that, one must have a fundamental understanding of the factors that influence the performance of the bonded joint so that variation in those factors can be parameterized and assessed. If one or more of the key constituents are changed, the combination is considered to be a "new" bonding system. Changes require test substantiation to verify that those changes result in acceptable performance of the bonded system.

3.0 DESIGN AND ANALYSIS CONSIDERATIONS

Analysis of a bonded joint includes consideration of configured structure and loading, understanding potential damage modes, and stress/strain and/or fracture-based substantiation using standardized analysis tools. Designing and substantiating a sufficiently strong structure as delivered is only the first step to ensuring the safe long-term operation of the aircraft.

Stress-based analysis methods typically focus on pristine structure without flaws (initiation analysis), while fracture-based methods assess the potential for damage growth from existing flaws or singularities within the structure (propagation analysis). Historic bonded joint analysis has typically utilized stress-based methods, ranging from simple load/area stress check to detailed derivation of bondline stress and strain distribution [10]. Many historic stress-based methods were unable to directly account for secondary loading effects outside the primary shear loading of the joint. These structures typically relied on the use of good joint design principals [11] to minimize the secondary induced tension loads that can serve as the primary driver of failure if not controlled.

Consideration of imperfections is an important aspect of the analysis and substantiation of structural bonded joints. Imperfections can be introduced during manufacture due to voids and inclusions or generated in service due to damage. The size and nature of imperfections that must be considered is an important and challenging aspect of the certification of bonded joints, but methods exist to determine the strength of a bond with a predefined damage feature. One method for the analysis of bonded joints utilizes a fracture-based failure criteria to assess the potential of damage growth from pre-existing flaws in the structure [12].

4.0 RIGOROUS EVALUATION OF VARIABLES

A wide array of testing methods are used throughout the development and execution of an adhesive bond. Testing is done to characterize the properties and behaviour of adhesives and substrates, the effectiveness of surface preparation, and the properties of the resulting bond. Testing is used to understand and guide the development of new processes and to ensure that existing bonding processes are performing as intended.

4.1 Targeted Test Methods

Tests can include materials characterization methods that assess chemical composition, cure kinetics, and physical properties before, during, and after cure. Surface preparation testing assess features including surface morphology, the presence and removal of contaminants, surface energy, and chemical activity of the surface. Post-bond testing includes assessment of mechanical strength, environmental durability, and resistance to fluids and in-service aircraft conditions.

4.1.1 Screening Tools

A battery of mechanical test methods have been developed to interrogate the integrity of adhesively bonds in an efficient manner. These rapid test methods were established for a diverse spectrum of objectives, including static adhesion, long term bond durability, and adhesion screening of built parts. One method, called the Rapid Adhesion Test (RAT) [13], uses a simple variations on the ASTM D 1781 climbing drum peel test to [14] make it applicable to composite materials and obtain qualitative assessments of adhesion, Figure 4-1. This test is useful for rapid developmental screening of adhesion of a system of variables and can provide rapid qualitative assessment of surface preparation-adhesive-substrate process combinations.

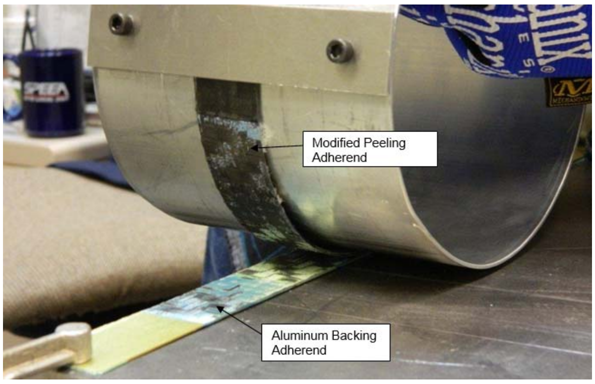

Figure 4-1. Rapid Adhesion Test using a 152.4 mm (6-inch) diameter drum. Notice how the peeling adherend of the coupon is inserted through a slot in the drum and how the backing adherend is clamped to the table.

4.1.2 Operationally-Based Assessments

In order to predict the performance of the bonded joint over the lifetime of the airplane, one must simulate and test the predicted loading mode, level of loading, static and fatigue effects, and exposure environment that the part will see during in-service use [15]. Typically, Mode I (cleavage/peel) or Mode II (shear) tests are used to evaluate the performance of the bonded joint. Mode I testing is especially important in assessing adhesion performance because it has historically proved most sensitive to changes at the interface. Even if it is anticipated that the bonded joint will see primarily Mode II shear loading, it is important to include some

Mode I tests in a thorough bond evaluation program to ensure adequate adhesion at the interface.

Not unlike many metallic materials, the measured toughness of a composite bonded joint may change as damage grows. Typically this is the result of an evolution in the micromechanical nature of the crack interface. The Double Cantilever Beam specimen is a well-established method to characterize Mode I fracture toughness, Figure 4-2.

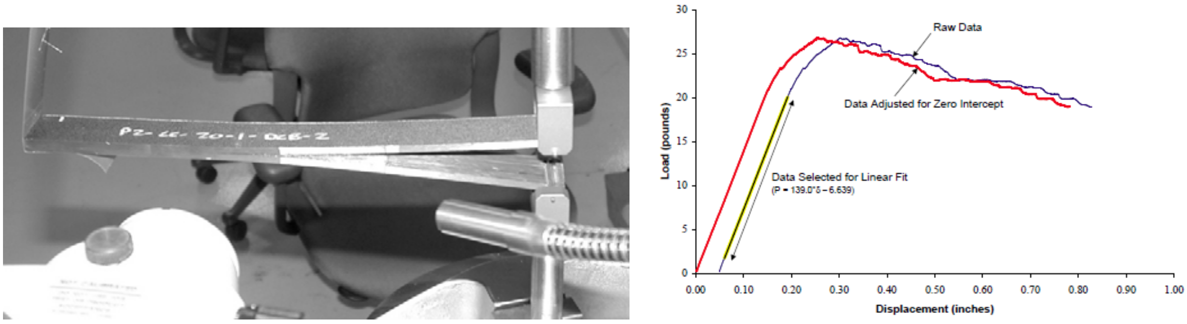

Figure 4-2. Double Cantilever Beam testing of composite adherends defining displacement induced fracture toughness characteristics.

4.1.3 Failure Mode Evaluations

The evaluation of failure mode is an essential part of characterizing the performance of a bonded joint [16]. Structural qualification of a bonding system requires both acceptable bond strength and an acceptable failure mode. Adhesion failure is indicative of an uncontrolled and unacceptable bonded system. Failure mode analysis of composite bonded joints becomes more complicated due to multitude of failure loci. An acceptable failure mode can occur within the adhesive, traditionally referred to as cohesion failure, but acceptable failures can also occur in between the plies or within the plies of the composite laminate and are referred to as inter/intralaminar failures, Figure 4-3. Adhesion failure modes at the interface are sometimes easy to define, as when the impressions of the peel ply fabric are observed, but other adhesion failures are more difficult to distinguish. The use of image analysis techniques, such as Image J, can provide help in quantifying these types of failures and provide valuable assistance in characterizing the bondline.

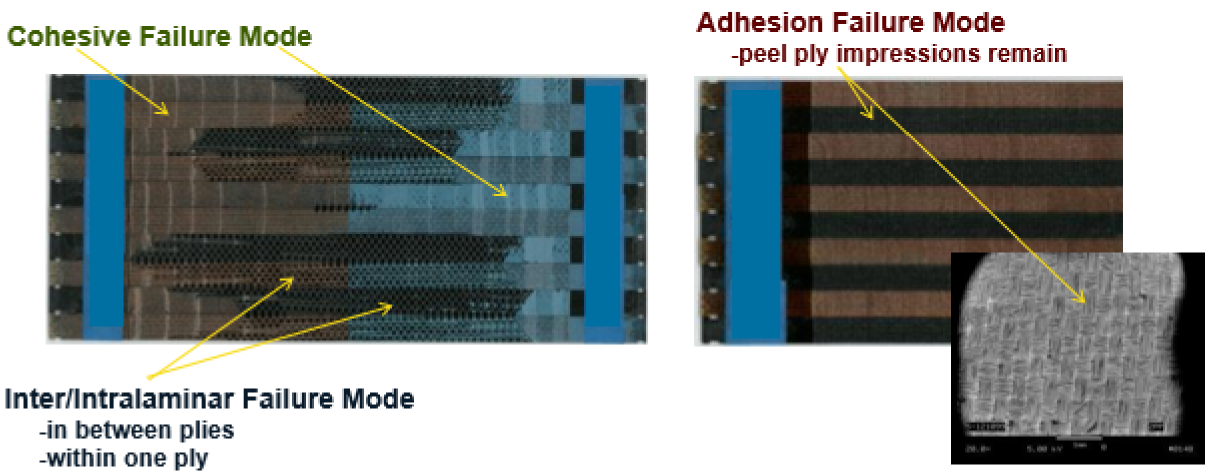

Figure 4-3. Failure mode characterization of CFRP Double Cantilever Beam test panels

4.1.4 Simulated In-Service Environments

Understanding the environmental conditions where the bonded joint will be used enables one to choose appropriate materials, processes, and designs that ensure a durable bonded joint. Environmental conditions can include temperature ranges, anticipated exposure to a hot/wet environment, humidity, salt spray, exposure to acidic environments such as SO_2, and exposure to typical aircraft fluids (fuel, hydraulic fluid, deicers, cleaning fluids, paint strippers, etc.).

The effects of environment and moisture on metal bonded structure have been studied over the years [17]. Moisture ingression into the bondline can result in corrosion at the interface and debonding of the structure. Specific test methods were developed for metal bonded systems, such as the wedge crack test [18], that characterized the resistance of the bonded joint to environmental conditions and have resulted in improved surface preparation methods and robust adhesives that provide durable bonded structures.

Test methods developed for metal bonded systems, however, are sometimes inadequate for composite bonded joints. For example, the gauge sizes are large, moisture exposure times are very long, and the tests do not always interrogate the interface of interest. To this regard, new accelerated environmental exposure tests have been developed, such as the Back-Bonded Double Cantilever Beam Test (BB-DCB) [19]. The BB-DCB test was configured to reduce the long exposure times for ensuring full moisturization of composite bondlines. In this configuration a 2 ply – 2 ply composite layup is bonded in the appropriate test configuration and exposed to the intended test environment, Figure 4-4. Because of the thin composite adherends used, the time for full moisture saturation of the bonded laminate is on the order of days, versus months or even years for a full-thickness configuration. After appropriate exposure to full saturation, the thin bonded laminate is back-bonded to pre-cured laminates of the thickness needed to provide the stiffness of the overall specimen, and the resulting bonded specimen is tested per the usual DCB methodology.

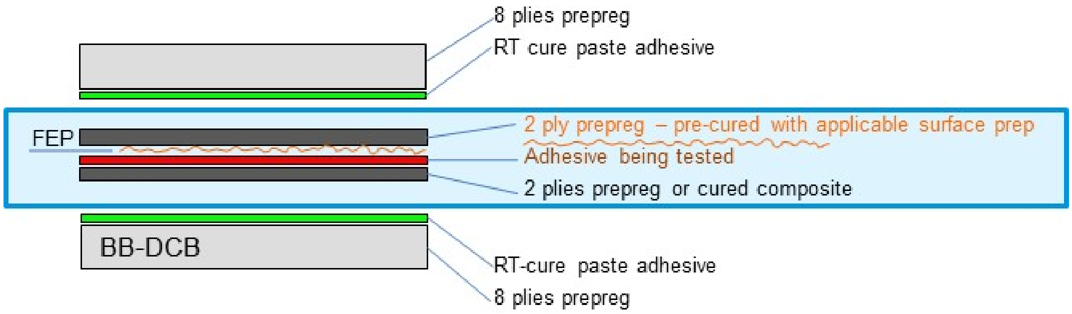

Figure 4-5. Back-Bonded Double Cantilever Beam configuration for accelerated environmental exposure testing of composite bondlines.

In addition to these techniques, the industry is assessing whether variation of the metal wedge crack test can provide useful information for composite bonds [20]. Composite characteristics, such as the flexural stiffness of the composite adherends and fiber orientation adjacent to the bonded interface must be considered in devising such a test.

4.2 Process Parameter Box

Testing to demonstrate the reliability of a proposed bonded system must include consideration of potential interactions between individual process parameters. As testing every permutation of conditions would lead to an excessively large test matrix, prior experience with similar materials and processes should be used to identify those combinations of factors that are most likely to challenge the reliability of the bonding process. Particular attention must be paid to the conditions that are expected to be experienced during manufacture of final parts, which may be challenging or time consuming to reproduce in the laboratory. Factors such as slow heat-up rates, step cure heating profiles, and extended time at temperature are frequently required to accommodate manufacturing realities but have been shown in the past to negatively impact resultant bond strength.

5.0 BOND PROCESS MONITORING

Bond process assessments can ensure that the manufacturing steps taken during the adhesive bonding process are performed correctly. In-process monitoring can be used to provide a record of Quality Control measures used to verify and archive the bond process. Various methods can be used for the verification, including buy-offs by quality control inspectors, cure-record charts, and automated systems. These can be integrated together in a computer controlled vision system that documents the entire bond process.

5.1 Surface Measurements

Certain steps of the bonding process are known to be very critical to the performance of the bond, such as the surface preparation step. New tools have been developed that can assess surface qualities that can be correlated to the performance of the bond, Figure 5-1 [21]. While not sufficient by themselves as a measure to validate the performance of the bonded system, they can be part of the overall protocol for ensuring bond quality.

Possible methods that can be used to verify acceptable prebond surface preparation of composite and metal substrates include visual inspection, contact angle analysis and surface energy measurements, infrared spectroscopy, and emerging methods such as inverse gas chromatography.

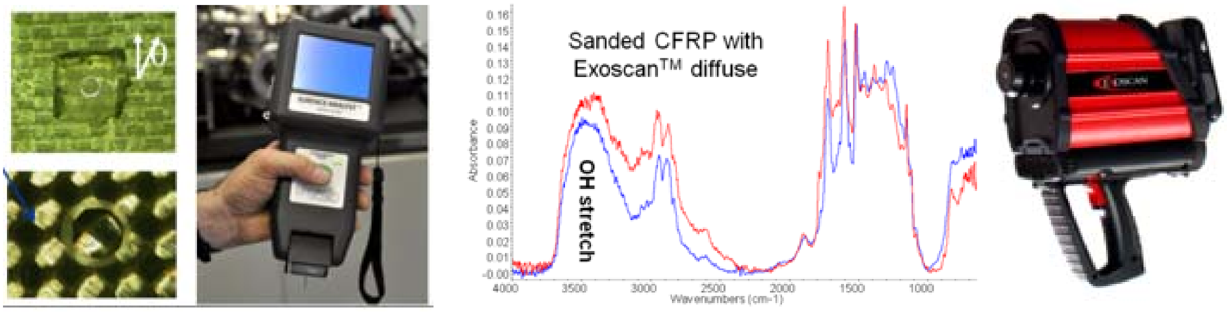

Figure 5-1. Contact angle analysis (left) and surface infrared spectroscopy measurements (right) can be used as part of a surface preparation validation scheme.

5.2 Bond Process Conditions

Due to the lack of mature non-destructive methods for direct and definitive assessment of the integrity of a manufactured bond, establishing and maintaining the integrity of the bonding process is the primary method to achieve the highest reliability in a final structure. Bond process validation can include adhesive, substrate, and process material quality receiving inspections, out-time and storage documentation, prebond moisture control, correct layup and assembly, consolidation, cure process monitoring, and bondline validation.

A stepwise method for implementing process control can reduce risk in a bonded joint fabrication process. The stepwise method included risk analysis for identification of defects with the highest impact and likelihood to occur, evaluation of various pre-bond surface analysis tools to monitor for the selected defects, and demonstration of the benefits of in-process monitoring utilizing threshold limits determined from bond performance tests.

In-process monitoring provides process data for in-line process checks as well as quantitative measurement records for statistical process control. Methods have been developed to integrate the data and provide automated documentation. These data can be used to generate a digital thread for troubleshooting of downstream problems, if needed. Features such as checks for materials, gloves used, surface preparation measurements, materials alignment, removal of peel ply and backing paper, adhesive out-time data, process sequence, and process anomalies can be captured using an optically enhanced bonding computer workstation system, Figure 5-2 [22]. In this system, a camera and LabVIEW framework were developed for guiding and monitoring an entire bonding operation. A hands-free, voice control mode of operation was incorporated for navigating through the LabVIEW program.

Figure 5-2. Optically Enhanced Bonding Workstation for Bond Process Control.

This type of system supports statistical process control by capturing measurable data. It is relatively inexpensive, reduces quality assurance inspection time, and enhances training.

5.3 Reliability Assessments

Reliability assessments, such as Bayesian Networks, allow for bonding process trade studies to be conducted to develop the best approaches for cost-effective Quality Control and create targeted reliability data validated with test data.

The purpose of performing a risk assessment is identification of high risk process parameters that are most likely to affect the overall quality of the bonded joint. These are the parameters that should be included in a monitoring and process control program. Several methods are available in the industry for performing a risk assessment, including Bayesian analysis [23] and fault tree analysis. In each of the risk assessment methods the results are based on inputs from subject matter experts which should be reassessed periodically based on new information, process improvements and learning curve maturity as the process develops.

6.0 POST BOND EVALUATIONS

Post-bond evaluations test the quality of the bond at the conclusion of the bonding process. Techniques used here can also be used to test how the quality of the bond is maintained throughout the lifecycle of the bondment.

6.1 Nondestructive Test Methods

There are several reliable nondestructive tools for assessing the quality of a bondline [24]. Methods include the use of ultrasound, to verify interfacial contact and check for voids, disbonds, inclusions, and porosity. Localized damage may also be assessed using alternative methods such as bond testers, shearography, thermography, and air coupled ultrasound technology. Each method has different capabilities and limits. A reliable Nondestructive Inspection (NDI) technique is part of the overall bond reliability assessment.

6.2 Bond-Strength Characterization Methods

Bond integrity determination through inspection has long depended upon the ability to measure the strength of an adhesive bond and to detect weak or “kissing bonds”. These weak bonds often do not show up using standard NDI methods until a stress is induced and an actual disbond and void occurs. Traditional nondestructive evaluation (NDE) methods are capable of measuring bond defects such as adhesive voids and disbonds, however they are not able to measure the bond strength. This limitation often leads to bonded structure being designed to a fail-safe capability, adding weight and limiting cost savings advantages.

To address these issues, the use of high intensity stress waves formed by pulsed laser excitation has been developed as a method to test for the strength of bonded joints. This laser bond inspection (LBI) approach uses a high peak power short pulse laser to perform a localized proof test of a bond. The method can be applied nondestructively to strong bonds but will fail a weak bond, creating a detectable internal disbond. Tests have shown the method to be sensitive to weak bonds in carbon fiber reinforced polymer (CFRP) composites structure bonds created by poor adhesive mixing, improper surface preparation or contamination. The LBI approach has so far shown that it is the only known nondestructive method with this capability that has the potential to validate the strength of bonded structure without full scale proof testing.

Development of the LBI method within Boeing has been well documented [25], and other aerospace manufacturers have shown interest in LBI studies as well. In reports by these organizations, the basic technical method employed is the same. The laser energy passes through a transparent tamping layer and is absorbed in an ablative layer placed on the part under test. The compression wave is transmitted and reflected back as a tension wave based on the material parameters. For transmission, the wave interacts at the adhesive to second adherend interface. When the tension wave reaches the bondline it will interact with the bond as a dynamic tension test with intensity and duration based on the laser fluence and pulse width employed in the test. The tension wave is created which will not affect a nominal strength bond, but will pull apart a weak bond creating a localized disbond (<10 mm), which is then detected by post-test NDI, Figure 6-1.

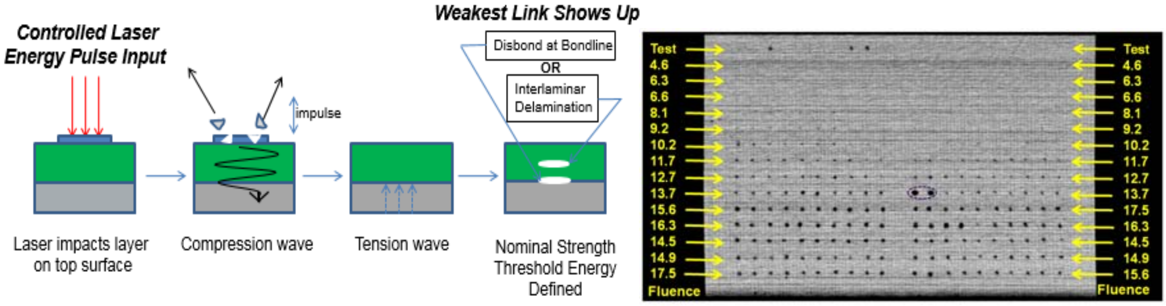

Figure 6-1. Laser Bond Inspection (LBI) method (left) for assessing weak bonds in composite bonded structures; NDI (right) of repeated LBI testing of a bonded sample at variable laser fluence levels.

7.0 DEMONSTRATION OF INTEGRATED CONCEPT ON LARGE

STRUCTURES

Throughout the development of new bonded structures, a building block substantiation approach is used starting --- with standardized engineering methodologies. Recent and soon to be released updates to the content provide significant new information on the design, fabrication, and testing of bonded structures. Other organizations, such as the Association for Standard Test Methods (ASTM) and Society of Automotive Engineers (SAE) standards, can provide valuable supplements to create a network of resources for the industry to share common tools and methods for the production of safe and reliable adhesively bonded primary aircraft structures.

8.2 Industry Collaborations

While often in steep competition in areas of aircraft sales, the industry works in a collaborative fashion on issues of system safety and reliability. Collaborative Centers of Excellence, including the FAA Joint Advanced Materials and Structure (JAMS) [27] investigate and share solutions to problems associated with the use of composites and advanced materials for large transport commercial aircraft, including researching the fabrication and deployment of safe and reliable bonded structures.

The National Aeronautics and Space Administration’s (NASA) Advanced Composite Program (ACP) is a consortium tasked to reduce the amount of time that it takes to get advanced composites from development and certification to the market and includes a large portfolio of tasks devoted to the understanding of bonded structures [28].

9.0 SUMMARY AND CONCLUSIONS

To satisfy regulatory and internal company requirements related to the performance and validation of structural bonded joints in certified aircraft products, the combination of materials and processes that make up a bonded joint must be considered as a coherent and controlled system. This paper describes the guidance on the definition, development, and maintenance of these bonded systems to ensure reliable performance throughout the product life cycle.

REFERENCES

1. (a) Higgins, A., “Adhesive Bonding of Aircraft Structures”, Intl. J. of Adhesion and Adhesives, Vol 20:5, 2000, pp 367-376; (b) Piehl, M. J., Bossi, R. H., Blohowiak, K. Y., Dilligan, M. A., Grace, W. B., “Efficient Certification of Bonded Primary Structure”, *SAMPE 2013 Conference and Exhibition*, Long Beach, California, May 6-9, 2013. Society for the Advancement of Material and Process Engineering. CD-ROM—10 pp.
2. (a) 14 CFR 25.605, Federal Aviation Regulation, “Fabrication Methods, Oct 30, 1978; (b) FAA Advisory Circular AC 20-107B – “Composite Aircraft Structure”, Sept, 8, 2009.
3. PS-AIR-20-130-01, “Bonded Repair Size Limits”, FAA, Nov 24, 2014.
4. Department of Defense, Joint Service Specification Guide (JSSG) – Aircraft Structures 2006, October 30, 1998.
5. Driver, D., “Adhesive bonding for aerospace applications”, 1995. In: Flower, H.M (ed) High Performance Materials in Aerospace, Springer, Dordrecht.
6. (a) Ritter, G. W., Blohowiak, K. Y., Pocius, A. C., Schueneman, G., “Adhesive Bonding of Metals”, AWS Welding Hbk 9.3, Chapter 10, American Welding Society, 2007; (b) Bossi, R. H., Piehl, M. J., “Bonding Primary Aircraft Structure: The Issues,” Manufacturing Engineering,

March 2011, pp 101-109; (c) Blohowiak, K. Y., "Challenges in Aerospace Metal Bonding", 2014, FAA Bonded Structures Technical Interchange Meeting, Salt Lake City, UT.

7. Potter, D. L., et al, Primary Adhesively Bonded Structure Technology (PABST), DTIC ADA082078, Nov 1979.
8. Seneviratne, W. P., Tomblin, J. S., Cravens, T. "Durability and Residual Strength Assessment of F/A-18 A-D Wing Root Stepped-Lap Joint", AIAA Centennial of Naval Aviation Forum #2011-7032, 21-22 Sept, 2011, Virginia Beach, VA.
9. Hart-Smith, L. J., Redmond, G., Davis, M. J., "The Curse of the Nylon Peel Ply", *SAMPE 1996 Conference and Exhibition*, Anaheim, California, March 25-28, 1996.
10. (a) "Methods of Analysis and Failure Predictions for Adhesively Bonded Joints of Uniform and Variable Bondline Thickness", DOT/FAA/AR-05/12; (b) Park, M., Frey, K. Simon, L., "Modeling and Analysis of Composite Bonded Joints", Amer. J. of Mech and Ind Eng, Vol 2:1, 2017, pp 1-7.
11. Hart-Smith, L. J., "Bolted and Bonded Joints, ASM Handbook: Composites, Engineering Mechanics, Vol 21, ASM International 2001, pp 271-289.
12. (a) "Fracture Mechanics for Composites", NASA Report 20080014103, 2008; (b) Hoyt, D. M., Ward, S., "Composite Bonded Joints Analysis, Data, and Substantiation, FAA Bonded Joints Workshop, June 16-18, 2004.
13. Blohowiak, K. Y., VanVoast, Peter J., Osborne, John C., Belcher, M. A., "Rapid Test Methods for Adhesives and Adhesion", 2013, SAMPE Proceedings, Long Beach, CA
14. ASTM D1781-98 (2012), "Standard Test Method for Climbing Drum Peel for Adhesives", ASTM Subcommittee D14.80.
15. Dillard, D. A., "Advances in Structural Adhesive Bonding", Woodhead Publishing Limited, Virginia (EEUU), 2010.
16. Davis, M. J., Bond, D. A., "The Importance of Failure Mode Identification in Adhesive Bonded Aircraft Structures and Repairs".
17. (a) Adams, R. D., Comyn, J., Wake, W. C., "Structural Adhesive Joints in Engineering", Chapman & Hall, London (UK), 1997.
18. ASTM, D3762-03 (2010), Subcommittee D14.80, "Standard Test Method for Adhesive-Bonded Surface Durability of Aluminum (Wedge Test)".
19. (a) Osborne, J. C., Blohowiak, K. Y., Piehl, M. J., Belcher, M. A., "On the Durability of Composite-Adhesive Bonds: Is Moisture the Enemy?", Aircraft Airworthiness & Sustainment Conference, April 15, 2014, Dallas, TX; (b) Van Voast, P. J., Blohowiak, K. Y., Osborne, J. C., Belcher, M. A., US Patent #9347868, May 24, 2016.
20. Adams, D. O., DeVries, K. L., Ricsi, D., "Development and Evaluation of Environmental Durability Test Methods for Composite Bonded Joints" Fall AMTAS Technical Review, November 2015.
21. (a) Kutscha, E.O., Vahey, P.G., Belcher, M.A., VanVoast, P.J., Grace, W.B., Blohowiak, K.Y., Palmieri, F.L., Connell. "Contamination and Surface Preparation Effects on Composite Bonding." *SAMPE Proceedings*, Seattle, WA, May 2017; (b) Chin, J.W., Wightman, J. P. "Roughness Factor for Wettability Adjustment." Composites, 27A, 419, 1996; (c) Boerio, F. J. , Roby, B., Dillingham R. G., Bossi, R. H., Crane, R. L. "Effect of Grit Blasting on the Surface Energy and Composition of Graphite/epoxy Composites." *SAMPE Long Beach CA.* May 1-5, 2005.
22. Wu, V., Bossi, R.H., Piehl, M. J., Savol, A.M., Forouhar, F, Manzer, P. "Method and System for Monitoring and Verifying a Manufacturing Process." Patent # 9,591,273, March 7, 2017.

23. Pado, Lawrence E. "Credibly Reaching a Reliability Target using a Model Initially Constructed by Expert Elicitation." *Integrating Materials and Manufacturing Innovation* 3:20, 2014.

24. a) Bode, M. D.; Holle, M. J.; Westlund, D.; DOT/FAA/ TC-14/39, FAA Report, August 2015. b) Hagemaier, D. J., "Adhesive-Bonded Joint", Nondestructive Evaluation and Quality Control, ASM Handbook, Vol. 17, pp 610-640, 1992.

25. a) Bossi, R., K. Housen, C. Walters and D. Sokol, "Laser Bond Testing," Materials Evaluation, Vol. 67, No. 7, pp. 819-827, 2009. b) Bossi, R, David Lahrman, David Sokol and Craig Walters, "Laser Bond Inspection for Adhesive Bond Strength," Proceedings of SAMPE, Long Beach, CA, 2011. c) Bossi, R., K. Housen and W. Shepherd, "Using Shock Loads to Measure Bonded Joint Strength," Materials Evaluation, 60, 11, pp. 1333-1338, 2002. d) Bossi, R., K. Housen and W. Shepherd, "Application of Stress Waves to Bond Inspection," Proceedings of SAMPE, Long Beach, CA, 2004.

26. https://www.cmh17.org/

27. http://www.jams-coe.org/

28. http://www/nianet.org/advanced-composite-consortium-acc/