A ROADMAP OF CERTIFICATION OF BONDED REPAIRS OF COMPOSITE AIRCRAFT STRUCTURES

Li, L.[1]*, Wang, J.[2], and Baker, A.[2]

[1] Aerospace Research Centre, National Research Council Canada, Ottawa, Canada
[2] Defence Science and Technology Group, Melbourne, Australia

* Corresponding author (Lucy.Li@nrc-cnrc.gc.ca)

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ABSTRACT

With the increased usage of fibre-reinforced composite aircraft structures, reliable repair technologies of primary structures are essential to ensure aircraft safety and availability. The application of bonded repairs of primary structures is limited due to strict certification requirement. This paper provides an overview of categories of damage and bonded repairs, and the challenges related to certification of bonded repairs of primary structures. A roadmap is proposed to enable certification of repairs carried out on critical primary composite structures for restoring their continued airworthiness, through a risk-based certification approach that certifies the whole repair systems through ensuring sufficiently high reliability of subsystems. Some aspects of the risk-based approach are highlighted, such as repair design and analysis, surface treatment, process control, automation, big data and Bayesian risk analysis, as well as structural health monitoring. Another strategy is "slow growth" approach, which allows for certification of bonded repairs based on the damage tolerance approach. Novel bondline design and crack arrest mechanisms have been proposed to ensure the requirement for damage slow growth management is met.

1. INTRODUCTION

Adhesively bonded joints have been widely used to join or repair fibre-reinforced composite components in aircraft structures. For bonded structural composite repairs, single or double-sided doubler patches, scarf or stepped patches can be bonded to the damaged structures [1]-[5]. As compared to repair procedures based on mechanical fastening, bonded repairs offer many advantages, such as better load transfer, improved aerodynamic performance, and weight efficiency. Bonded repairs offer broad applications, from non-structural repairs to those of load critical components. Bonded repairs to composites range from applications to thin monolithic structures, including sandwich construction, to thick primary structure and hybrid composite/metal structures. A similar range of metallic structures can also be efficiently repaired with bonded composite patches [6].

Due to their relatively low load transfer efficiency, when mechanically fastened repairs are the only option, composite aircraft structures need to be overdesigned. When bonded repairs are a viable solution on the primary composites structures a lighter and more efficient aircraft design can be achieved. This is an important issue for unitized large integrated composite structures, which are increasingly used and prohibitively expensive to replace.

There is a pyramid of damages and repair scenarios based on damage severity, frequency of damages, repair effort and certification challenges. Majority of bonded repairs are performed on relatively minor damages on secondary and tertiary structures, such as cuts, free edge and corner damages. Such repairs can be conducted according to standard procedures as specified on structural repair manual. More severe damages, such as visible impact damage and manufacturing process induced damages, do occur on primary structures. The top of the repair pyramid represents fewer but highly specialized repairs of critically loaded primary aircraft components. For a composite aircraft structure, Figure 1 illustrates the damage severity in relation to residual strength of a structure, as stated in *AC20-107B* [7].

It was well recognised that carbon fibre reinforced polymer composite laminates, as widely used on aircraft structures, have high fatigue resistance in fibre dominant load cases. As summarised in CMH-17 [8], the non-damage-growth criterion worked well for many composite structures. Likewise, repairs or replacement of damaged in-service structures are often required to restore static strength safety margins, well before the need to address fatigue performance concerns, a typical example being a composite structure with visible impact damage. However, it has also long been recognised that in some damage cases, most specifically delamination in laminates and disbond in bonded joints where the damage can grow under fatigue loading with the peak load significantly lower than the design limit load whilst the structure still maintains residual strength above the design ultimate load, a slow growth management approach could apply [9]. Such a damage tolerance management strategy may be beneficial towards reducing maintenance cost by delaying or avoiding unnecessary repairs or replacement of composite components. Since 2010 this slow growth management strategy has been considered acceptable by FAA, provided the damage growth is predictable [6, [8].

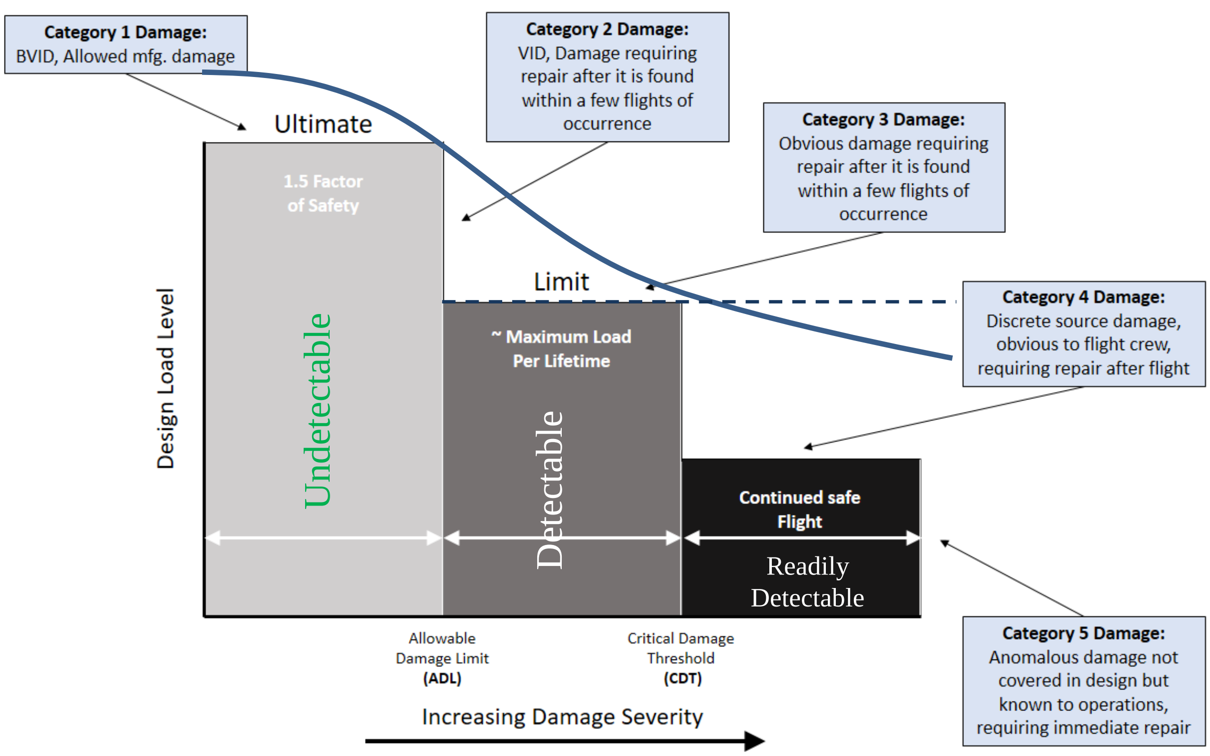

Figure 1. Damage severity and design load levels chart [7].

With increasing usage of large, complex composite aircraft structures, many in aerospace industry agree that the full cost and weight savings of composites cannot be realized until bonded joints can be certified without fasteners. As a result, technology development to prove the ability to quantify and predict bond reliability has progressive since the late 1990s, from early effort of Composites Affordability Initiative (CAI) by the U.S. Department of Defense (DoD), to more recent initiatives of the European Union (EU)-funded Boltless assembling Of Primary Aerospace Composite Structures (BOPACS) project, DARPA Transition Reliable Unitized Structure (TRUST) program led by Lockheed Martin Aeronautics, and ongoing effort at NASA, Boeing, Airbus [10]-[16]. The effort in building a certification regime for bonded primary structures shine lights on the roadmap development of certification of bonded repairs of primary composite structures.

2. CHALLENGES WITH BONDED REPAIR ON PRIMARY STRUCTURES

Adhesively bonded repairs have been successfully applied to aircraft primary structures, saving hundreds of millions of dollars and significantly enhanced aircraft availability [45]. A long list of such applications is provided in Reference [46], including repairs on F111, C130, P-3C, F/A-18, Mirage III and many other aircraft.

In most applications of the bonded repairs of primary structures, the residual strength of the damaged structures, in absence of the bonded repair, was higher than the design limit strength multiplied by a safety factor, as required by the certification regulations.

The following discussion will focus on the most challenging certification scenario, that is, certification of bonded repair applications to damaged primary structures that have low residual strength.

The bonded patch repair for F111 lower wing skin crack was an example where the residual strength of the structure prior to repair was lower than the design limited load. Certification of this repair was based on a detailed design and testing program followed by a proof test with full structure loading, which was very costly [47] so could only be justified when several aircraft require repair or reinforcement.

So far, a bonded only repair is not permitted without a proof test, when the structure in the absence of the repair could not meet the residual strength requirement. The current certification requirement mandates the redundancy in load-carrying capability of a primary structure, where the failure of the bond could not jeopardize the safety of the aircraft.

When residual strength does not meet the current certification requirement, bonded repairs can be used on primary structures of an aircraft when the residual strength is enhanced through alternative load paths, e.g. through mechanically fastened or bonded-mechanically fastened hybrid repairs. Provided the fasteners can restore a limit load capability in the absence of the adhesive bond.

With regards to certification, credits are not given to the adhesive bond for restoring structural integrity[1]. Behind the conservatism of the current certification philosophy is lack of confidence in bond reliability and durability. As such, it is stated in AC 20-107B "Composite Aircraft Structure," issued jointly by the Federal Aviation Admin. (FAA,

[1] However, credit can be given to the adhesive bond for stress reduction during the cumulated flight hours between when a bonded reinforcement is applied and when the bonded repair is inspected to be sound. This is the critical factor indicating a reinforcement can extend fatigue life of a structure (refer to [27] for more detailed information).

Washington D.C.) and the European Aviation Safety Agency (EASA, Cologne, Germany), that there are three options for certifying damage tolerance of structures with bonded joints – crack arresting features, non-destructive methods for bond strength measurements, and proof testing [5].

Structural bonded repairs, especially of primary structures, pose major scientific challenges with existing repair technologies [18]. There has been research into nondestructive testing or inspection (NDT/NDI) such as ultrasonic approaches for bond strength measurements [19]-[22]. These NDT/NDI approaches do not offer direct measurements of bond strength; rather they attempted to correlate acoustic or other signals with bond interface characteristics. For example, nonlinear acoustic measurements explores highly nonlinear behaviors exhibited by a weakly or incompletely bonded interface through modulation of ultrasonic waves [19]. No proven NDT/NDI technologies have been validated for their capability to quantify strength and durability of bonded joints yet, since they cannot develop sufficiently high stresses to interrogate the bond. Proof testing, such as laser shock inspection [23] [24], holds promises for bond strength validation and verification. This method sends a significant reflected tensile load from a laser source directed onto the surface of the bonded joint to provide a pass and fail test of bond strength, based on subsequent ultrasonic inspection. However, it is not a direct testing method because the laser energy to simulate a mechanical load is calibrated through lab test samples. Repeatability and reliability of this method for quantitative bond strength prediction or correlation are yet to be fully established. Furthermore, laser shock inspection is not only prohibitively expensive, its application in a non-depot repair environment could be hazardous to operators. A practical and cost-effective option is the periodic proof test of bonded repair coupons (BRCs) [25] [27]. The BRCs are made of the same material as the repair patch, and are bonded concurrently with the patch, and therefore, as far as possible, under identical conditions to the repair patch. This test is based on the assumption that the bond strength of the BRCs represents the bond strength of the patch. Strength tests of the BRCs after the repair application and during the service life could help determine the strength of the bonded repairs. Extensive assessment of the approach was reported in [28] and this method was concluded to be promising. Before viable NDI or proof testing method are accepted, the only option left is failure prevention by design features. As a result, mechanical fasteners through the bondline thickness (or so called "chicken rivets") have been the choice for bonded joints and bonded repair of primary structures, to act as damage arrest mechanisms and as an alternative load path to carry limit load should the bond fail. Research reported in [29] indicated that in a well-designed hybrid bonded joint/repair, the mechanical fasteners could effectively increase the fatigue life of the joint/repair in addition to providing residual strength in the case of bond failure. Another type of hybrid repair, combined with adhesive bonding and damage optimum cut-out, has also been reported to meet the certification requirement for repairs of primary structures [29].

With the increased usage of large, unitized composite structures on airframe, certification of bonded joints and repairs of primary structures is on a case-by-case basis. There is a need for coordinated certification system for bond repairs, as well as bonded primary structures on civil transport and military aircraft.

3. CERTIFICATION STRATEGIES OF BONDED REPAIRS of PRIMARY COMPOSITES STRUCTURES

Two potential alternative means of compliance are explored to certify bonded repairs of primary structures for the purpose of restoring load carrying capability above the limit load. The real solution may require both approaches to achieving the eventual acceptance from certification authorities.

- Risk-based certification approach through quality control and bond qualification for certification of bonded repairs, and/or
- "Slow growth" based bonded repair on primary structures.

3.1. Risk-based certification approach for primary structure bonded repairs

To explore the possibility of deploying bonded repair without mechanical fastening on single load path primary aircraft structures, a risk-based certification approach is proposed. The key barrier to certification of bonded repair is weak bond, which cannot be easily detected. The principle of risk-based approach is to quantify the entire bond system through quantifying each individual subsystems [9]. This approach is based on the risk analysis to achieve sufficiently high reliability in bond strength and durability through state-of-the-art process control of each step and every aspect of a bonded repair. As compared to certifying bonded joints on primary aircraft structures, bonded repairs come with additional challenges. Repairs that are performed in the field or a hanger facility may not have the same level of environmental control as a manufacturing facility. Each repair is specific to the damage type, location and material systems of a structure. Nonstandard bonding processes are often needed, which could lead to bond quality issues such as void contents, non-uniform cure, and incomplete cure. Having said that, the fundamental technology development of bonded repairs and bonded primary structures to establish a certification process are the similar. The technologies will include damage assessment, repair design and optimization, material and process qualification, process control, and NDI/NDT methods for quality assurance. Bond durability is also important to quantify under design loading and typical in-service environments such as fluid exposure, and temperature and humidity cycling.

Surface treatment and process control

Quantifiable reliability of surface treatment is the key to a successful bond repair, and a critical subsystem towards risk-based certification. It was found that automated applications of energy-based surface treatments for chemical activation of a surface, such as atmospheric plasma and laser surface treatments, enable a high level of process control [32], [33]. Repeatability and reliability of process control can be achieved through the robotic control of critical process parameters such as energy level, standoff distance, raster speed and pattern to produce a desired quality of treatment. A combination of surface analysis technologies, such as contact angle measurement, Fourier Transfer infrared spectroscopy (FTIR), optically stimulated electron emissions (OSEE), and laser induced breakdown spectroscopy (LIBS), was often applied to correlate outputs with bond performance [33] [34]. There have been other surface treatment qualify assurance technologies, such as peel resistance measurement during the removal of a co-bonded cloth from treated surface as a mean to provide proof of bond quality and simultaneously serve as a surface pre-treatment for adhesive bonding [35].

It is worth nothing the importance of automation in achieving reliability of repair process control. Automation can be applied in many aspects of a repair process [35]. A laser scanner can be used to characterize damage surface profile with high accuracy; an automated milling process can be employed to prepare the surfaces for bonding with high reproducibility; robotized laser or open air plasma system can be operated to conduct surface preparation; the repair patch ply cutting can be done in an automated system; 3-D printing can be used to manufacture the mold for fabricating the repair patch; Inline ultrasound inspection and laser bond inspection can be performed for quality assurance. Automation mitigates process variability introduced by the operator and reduce process time, while generating data essential to risk analysis. The applications of automation was found to tremendously improve the quality and durability of the repair [36].

Linking process control to reliability

In a bonding process conducted under factory conditions, hundreds of steps or subsystems are involved and each is to be quantified to achieve bond repeatability and reliability [12]. To link process control to reliability, fault tree analysis and Bayesian network were the tools developed and used by Boeing and other organizations to build a certification system through identifying and quantifying strategy subsystems [12][13]. Fault tree analysis was conducted to map a bonding process, from material qualification to the bond inspection, to determine where and what types of quality checks are required. Inline inspection, such as FTIR surface analysis, and post-cure NDE/NDI and possibly including proof testing such as laser bond inspection repairs is the integral part of a certification bonding process to provide a quantitative assessment of process reliability of each subsystem. Other data such as adhesive out-time, temperature and humidity of the bond environment, temperature history, void contents, and other information pertaining to the bond process are integral part of the process management.

Big data generated from each repair process, including design, material and processes, process control and NDI can be managed and analyzed using Bayesian network or other risk analysis tools [9] [13]. The industrial 4.0 has led to digital transformation through automation, sensors and artificial intelligence to achieve quality, efficiency, and reliability of a process. It is recommended that thresholds of each subsystems be pre-determined and a quick systematic assessment of bonding process reliability can be performed [33].

The key question here is how many of these test approaches are feasible under repair conditions, specifically for critical repairs. Where it is only feasible to conduct a subset of these tests, it seems likely that certification of fully adhesive bonded repairs will require some form of proof test, such as the torque test which, although indirect, also allows ongoing evaluation of bond durability [26], and/or SHM, as discussed in the next section.

SHM and NDI for in-service bond integrity

Although In-service bond monitoring (safety by continuous inspection) is not part of the bond certification process, risk-based management strategy can be applied to ensure bond durability and continued airworthiness of the repaired structures. Structural health-monitoring technologies such as optic fibre for strain mapping offers excellent potential for in-flight monitoring of repair patches [37]. Other approaches such bond vacuum sensors, acoustic inspection, in combination with NDT/NDI, were also used for implemented to monitor in-service condition, damage and bond durability [18].

Overall, the risk-based certification framework through quantifying individual subsystems offers a coordinated way to potentially achieve reproducibility and reliability required for bonded repair on primary structures. Many technologies for process control and management already exist, and new technologies are expected to emerge and mature. It is true that, even if a high enough bond reliability is achieved, civil aircraft regulation may still not accept risk-based certification of bonded joints on primary structures in the immediate future. However, such certification approach may be viable to certify bonded assembly as well as repair for military aircraft, where risk acceptance level is often driven by mission requirements.

3.2. "Slow Growth" Based Bonded Repair on Primary Structures

Current composite aircraft structures are certified based on "no growth" philosophy, which requires that the stresses in the structure be kept below the threshold level that would result in any kinds of damage growth during the service life of an aircraft. A "slow growth" based bonded repairs is proposed for disbond or delamination growth on the basis of damage tolerance approach to certify bonded repairs of primary structures. As stated in AC 107-20B, damage growth of composite structures is permitted on the conditions that 1) the residual strength remains above limit load; 2) the growth rate is "slow, stable and predictable" and 3) an inspection program is developed consisting of frequency, extent, and methods of inspection. Although this "slow growth" approach may not be explicitly recommended for bonded joints on primary structures yet, it is conceivable that such certification approach may be acceptable should the aforementioned requirements are met. With this certification strategy in mind, two potential certification approaches and the knowledge gaps are proposed – "slow growth" based bonded repair and "slow growth" based hybrid repair.

As mentioned in Introduction, it has long been recognised that damage in bonded joints can grow under fatigue loading with the peak load significantly lower than the design limit load whilst the joint still maintains residual strength above the design ultimate load, and the damage growth is predictable [38], fulfilling a basic requirement to allow transition from a no-growth to a "slow growth" design or management basis. An assessment of fatigue life of bonded joints and patch repairs for primary airframe structures also suggests that the "slow growth" approach would be feasible for a bonded joint/patch repairs if the patch is designed to have sufficiently large transfer length to allow stable and extended damage propagation [37]. Other possibilities include fail-safe crack arrested bonded joint design, for certification of bonded unitized composite structures, where a reduced number of fasteners was achieved through placing the reinforcing fasteners selectively in the bondline [39]; for example to minimize peel stress.

Other novel bondline design were proposed to offer damage arrest, which could lead to slow, stable and predictable damage growth for the "slow growth" certification of bonded repair. A hybrid bondline concept [40], [41] was introduced as a crack-arrest feature by deploying both adhesive bonding and thermoplastic welding to the bondline, providing new mechanisms of energy dissipation. A similar bondline modification strategy was proposed [42] to enhance Mode II fracture toughness, when the joint is subjected to shear loading, by inserted a PTFE film inside the adhesive bondline during the bonding process to create sacrificial cracks inside the adhesive. This approach reduces strain concentration at the crack tip, and delayed the crack propagation. These proposed technologies are still at its early stage of development. Further demonstration and validation of their effectiveness as a crack arrest mechanism under representative loading and in-service environments are required. Other approaches such as through-thickness stitching and mechanical surface interlocking [15] [43] were also explored although most of these technologies are only suited for bonded joint assemblies. Another type of hybrid repair, combined with adhesive bonding and damage optimum cut-out, has also been reported to meet the certification requirement for repairs of primary structures [29], 48-50]. With this hybrid repair approach the inspection interval is determined based on the improved fatigue life of the structure that is provided by the optimum damage cut-out, in absence of the bonded repair.

Multiple key knowledge gaps are to be addressed in order to consider "slow growth" certification strategy for bonded joints. These gaps include damage characterization and relevant NDI capabilities, very limited information related to fatigue driven damage growth, among others [44]. Another key concern to bonded only "slow growth" repair method is damage mechanisms. When damage occurs in the composite structure or the patch itself, this "slow growth" approach applies as long as damage growth rate is proven to be slow, stable, predictable and readily detectable by NDI. However, if the damage occurs on the bondline due to poor design or poor repair process control, inadequate surface preparation or high humidity environmental during repair control, weak bonds may lead to failure of the entire bond, rendering this "slow growth" approach inapplicable. To minimize the risks of bond quality reliability, and risk-based methodology for process control, in conjunction of the use of bond strength measurement by NDE/NDT or proof testing, and SHM for in-service management will likely be a pre-condition for the "slow growth" certification approach.

4. SUMMARY

Adhesively bonded repairs have been successfully applied to aircraft primary structures, saving hundreds of millions of dollars and significantly enhanced aircraft availability. In most applications of the bonded repairs of primary structures, the residual strength of the damaged structures, in absence of the bonded repair, was higher than the design limit strength times a safety factor, as required by the certification regulations. In order to achieve its full potential, further research and development is required to enable the bonded repair to be certified when the residual strength is below design limit load.

This paper provides the state of the art of bonded repair applications and when credit is not given to bonded repairs to restore structural integrity of a primary structure. This paper proposes a roadmap towards building reliability and repeatability into bonded repair process especially for applications where damage has reduced residual strength below limit load, through a risk-based coordinated certification system. It also offers a "slow growth" certification process by incorporating novel bondline concepts and repair design. However, this approach is only relevant where bond strength and durability are validated through some of the processes described. It is worth noting that there remain tremendous hurdles in certifying fully bonded repairs of primary structures with residual strength below design limit load, and further research is needed to address the gaps.

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