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Advances in the proof test for certification of bonded repairs – Increasing the Technology Readiness Level

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ABSTRACT

The availability of an efficient, cost-effective repair technology is an important maintenance requirement to restore structural integrity to metallic and composite airframe structures damaged in service. Generally repair involves attachment of a reinforcing structural element or patch to replace the damaged load path. Traditionally, the reinforcements are attached to the structure with rivets or bolts; however, attachment by adhesive bonding offers many structural and cosmetic advantages.

However, bonded repairs of primary structure are very difficult to certify this is because available non-destructive procedures, such as ultrasonics or thermography are unable to detect weak adhesive bonds. In view of the limitation of non-destructive inspection an alternative approach is to directly apply stress to the actual repair bond region or to a very close simulation of the region.

In this paper, further work is documented on a proof test of bonded repair coupons (BRCs) that are bonded to the parent structure at the same time as bonding of the repair patch. Therefore, the BRCs are close representation of the actual repair bond strength. To assess the bond strength, immediately after patch application and also possibly through the life of the repair, the BRCs are subject to a previously determined proof load in torsion.

The aim of the study is to improve the Technical Readiness Level of the test when applied to various parent-structure/patch-repair systems, including carbon-epoxy/carbon-epoxy; aluminium/boron-epoxy and aluminium/aluminium. Improved BRC application methods were developed to increase the reliability and consistency of the results, and sensitivity to cure condition, surface treatment, contamination, and fatigue damage were evaluated.

A detailed finite element (FE) study was undertaken to: a) simulate stresses in the BRC, adhesive and parent structure during the proof test, b) compare the stresses in the patch and BRC when the parent material is under stress and c) investigate the influence of BRC proximity to the patch tip when the parent material is under stress.

A conclusion from the FE analysis and fatigue study was that a BRC with the appropriate ply configuration could represent the bondline stresses experienced at the patch tip, and hence could also be used to monitor fatigue damage.

1. Introduction

When composite airframe structures suffer visible damage, the structure must be repaired to restore structural integrity [1]. Repair generally involves damage removal followed by installation of a reinforcing patch or doubler to reinforce and restore the lost load path and thus restore residual strength to an acceptable level. A similar situation arises with metallic airframe structure. There are two main options for attachment of the reinforcement: mechanical fasteners and adhesive bonding.

Adhesive bonding has many advantages over mechanical fastening [2] including the potential for improved strength and fatigue resistance and minimisation of the need to further damage the structure by the formation of fastener holes. For thin-skin secondary structure, especially honeycomb panels adhesive bonding is the favoured approach. However, for repair of thick skinned (>3 mm) primary structure, while adhesive bonding retains its advantages over mechanical fastening the outcome is not so clear primarily due to the inability of non-destructive inspection (NDI) to adequately assess bondline quality including, for example

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adhesive undercure. Generally, however, most major defects such as macro voids and disbonds can be readily detected.

Of major concern are very weak bonds called “Kissing Bonds” which are very difficult to detect by ultrasonic inspection [3] since the surfaces are in intimate contact, or perfectly coupled with a liquid, such as water infiltrated by capillary action.

During manufacture material and process control, staff training, oversight and regulation all help minimise the risk of weak bonds forming during bonding processes; however, this level of control is particularly difficult to achieve in a repair situation. Hence, the inability to detect weak bonds is a severe limitation which causes considerable difficulties in airworthiness certification for bonded repairs of primary structure [4]. The outcome is generally that bonded repairs can only be accepted to primary structure on the basis that the repaired structure can withstand “Limit Load” (possibly with a safety margin) in the absence of the reinforcing patch or (partial damage thereof within the extent of damage-arresting features), thus limiting the size of damage that can be repaired by bonding [5]. Limit Load is generally defined as the highest load expected in the life of the aircraft.

Clearly then a reliable ability to detect weak bonds both directly after application and then during the life of the repair would considerably increase the scope of bonded repairs for primary structure. In a recent review [6] the authors identified and discussed the few potential solutions currently under exploration.

The aim of this paper is to document progress in maturing the Technical Readiness Level (TRL) of the BRC proof test, in part focusing on invited comments from experts in structural bonding and structural repairs.

2. The proof test

FAA AC20-107B [7] identifies three ways to substantiate a bonded joint for primary structure, based on requirements set forth in 14 CFR § 23.573(a). When applied to repairs, the first approach is to demonstrate limit load capacity assuming disbond of the repair, or damage to the extent of debond-arresting features, as adopted in the Bonded Repair Size Limit policy [5]. Validation by reliable inspection is a second means, however there is currently no suitable accepted inspection technology [12]. Hence for large damage, the third option of proof testing by direct mechanical loading, may be the only acceptable means of certification [6]. Direct loading of the whole patch will be infeasible in most cases, and may be considered too expensive or impractical for real-world application. Furthermore, proof tests conducted at a sufficiently high load to interrogate repaired structure could be damaging and impact on future performance of the repair.

The BRC proof test [8] is potentially a more practical and cost-effective option, whereby BRCs made of similar materials to the repair patch are bonded simultaneously with and therefore under conditions that are as near as feasible identical to the repair patch. The aim of the test is to establish that the BRCs, and therefore by inference the patch, have achieved and subsequently maintained in-service an acceptable level of strength.

Assuming all technical and practical challenges with the method can be overcome, the limiting factor on acceptance of the method is the degree to which the strength of the BRCs can be accepted as accurately representing the strength of the repair. In the approach developed in Ref. [8] a thin BRC is subjected to shear loading, which was applied through an adaptor, using a torque wrench. The adaptor is bonded to the BRC with a relatively weaker adhesive and subsequently removed after warming; Fig. 1 provides a schematic of the test configuration. Mechanically, this approach is very similar to a standard (ASTM E229) test called the Napkin ring test which involves applying torsion to end bonded metallic tubes. The ASTM test is mainly used to measure shear modulus, yield stress and strength of adhesive films.

The BRC is bonded to the parent structure over a narrow annulus, whilst the adaptor is bonded over the whole surface of the BRC. This allows use of a weaker adhesive and has other practical advantages, such as a fast cure time (hence reducing process duration) and low T_g (hence lowering temperature for removal of torque adaptor). After each proof test (assuming no failure) the adaptor is heated to ~80 °C and removed using the torsion wrench.

The aim of the test is to establish a proof torque for standard (un-degraded) patch/parent/adhesive combinations to provide a statistically sound basis for determining the degree of degradation of BRCs under the various test conditions.

The approach to estimating the proof torque is as follows: tests to failure are conducted on sets of BRCs applied under optimum bonding conditions in a controlled environment laboratory. From this data the proof torque is estimated from:

$$T_p = \bar{x} - t * \sigma$$

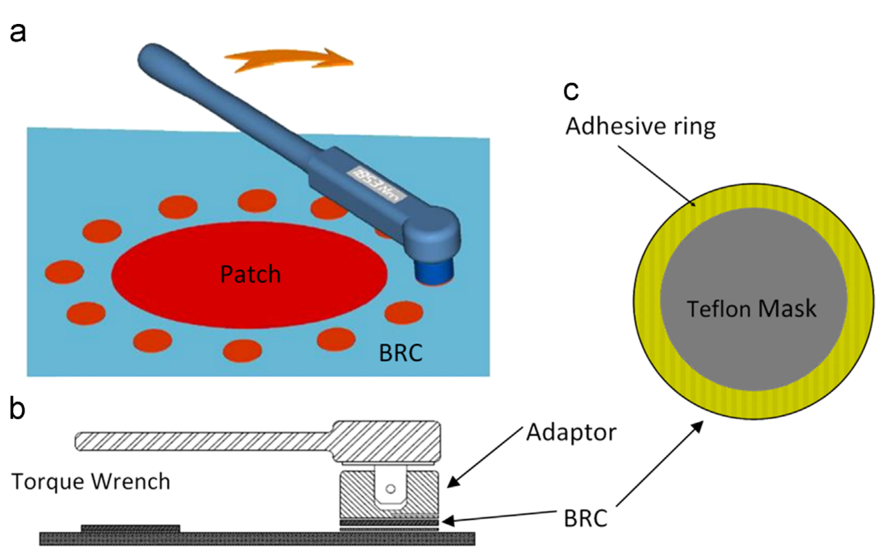

Fig. 1. (a) Repair patch and satellite BRCs, with one BRC under torsion test, (b) details of the BRC with adaptor required to apply the torsion loading and (c) configuration of the adhesive ring on the BRC inner surface bonded to the parent structure.