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Assessment of residual strength of repaired solid laminate composite materials through mechanical testing

P.G. Slattery, C.T. McCarthy, R.M. O'Higgins *

IComp: The Irish Centre for Composites Research, Materials and Surface Science Institute, Department of Mechanical, Aeronautical and Biomedical Engineering, University of Limerick, Limerick, Ireland

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ABSTRACT

Robust residual strength test methods are critical for assessing the validity of new repair techniques for restoring strength to damaged composite laminates. In this study, the strength of pristine, damaged and repaired solid laminate composite material has been investigated by performing four different mechanical tests. Impact damage was imparted to carbon fibre epoxy resin specimens using a drop tower instrument. Specimens were repaired using a novel resin injection technique employing a low viscosity adhesive as the repair resin. The compressive strength of specimens was determined using compression after impact (CAI) and large-scale CAI test methods. Tensile tests were performed to obtain tensile strength. Flexural strength was evaluated by four-point bend tests. The thoroughness of each test method in determining the success of the repair was investigated. This study demonstrates that the strength restoring capacity of a repair method is subject to the test method used to assess the residual strength. The four-point bend test was shown to be the best preliminary test method for screening repair techniques as it is not affected by loading anomalies. However, design criteria should always be considered when choosing a residual strength test method for assessing repair validity.

1. Introduction

Polymer-matrix composites (PMCs) are increasingly used in several industries as a replacement for metallic structures due to their high specific strength and specific stiffness [1]. Impact damaged PMCs contain complex failure mechanisms including delaminations, matrix cracks, fibre breakages and penetration [2,3]. Despite not always being visually detectable this damage can significantly reduce the strength of PMCs [4–7]. Repair of such damage is critical to ensure structural integrity of the laminate. While a number of repair strategies have been proposed, patch or scarf repair have found greatest application in the repair of impact damaged composite materials [8]. However, on thicker laminates scarf repair patches become excessively large, also in areas where aerodynamic efficiency is required doubler patches cannot be used [9]. In addition, the repair procedure requires a high degree of skill by the engineer carrying out the repair. There is still a demand for more efficient repair strategies, particularly for non-aerospace PMC applications. In this paper, the residual strength of composite laminates repaired using a novel resin injection technique is assessed using a variety of mechanical tests. The repair technique was developed to offer a non-invasive alternative to the resource intensive scarf repair technique, particularly for non-aerospace composites applications.

PMC laminates with quasi-isotropic stacking sequences are widely used in a variety of structural applications. When impacted these laminates exhibit damage consisting of delaminations with a conical shape emanating from the impact point, connected with some transverse cracks in the plies [10]. The size of the damage grows from the impact side to the rear side and may result in breakout. The resin injection technique developed allows these delaminations to be rebonded, while filling the transverse cracks with adhesive and realigning plies and fibres. However, fibre ruptures cannot be repaired. This is not seen as a disadvantage in relative terms when compared to scarf/patch repair as broken fibres, as well as undamaged areas, are removed using that technique and the success of the repair is dependent on the integrity of the bondline.

The validity of any repair technique is assessed on its ability to restore the strength and stiffness of the damaged structure to its original properties. However, the test chosen to determine the damaged/repaired residual strength can influence the assessment almost as much as the repair technique itself. Compression after impact (CAI) tests are widely used as a structural test for repaired

* Corresponding author.
E-mail address: ronan.ohiggins@ul.ie (R.M. O'Higgins).

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composite specimens as a large region of the specimen is subjected to the maximum stress resulting in a strenuous measurement of specimen compressive strength. Compressive strength is extremely sensitive to internal damage as compressive loading results in localised buckling of sublaminates [11,12]. In addition, composite structures generally perform less well in compression loading as the reinforcing fibres are susceptible to failure by microbuckling. A test rig is used during CAI tests to prevent the specimen buckling, simulating the behaviour of panels between stiffeners on an aircraft structure [10]. However, frictional effects between the specimen and test rig are not taken into account [13]. CAI testing is governed by ASTM standard D7137 [14], although several modifications to the test rig have been used to account for thinner specimens, end crushing and variations in specimen geometry [11,15–19]. One disadvantage of CAI tests is that the distance between stiffeners on aircraft fuselages is greater than the width of CAI specimens [20–22]. For this reason several authors have performed compression tests on specimens larger than those used in CAI tests [16–18,23]. In addition, as with all types of compression tests on composites, the anti-buckling guides used in the test may serve to increase the apparent strength of the test specimen [14].

Tensile testing of repaired specimens is performed to evaluate the success of the repair in accounting for fibres broken during the impact event. Repairs consisting of adhesive bonds are commonly tested in tension to assess the effect of design parameters such as scarf angle, bond length and patch lay-up [24–31]. Resin injection repair does not repair fibres broken during impact or replace broken fibres with additional fibres. Restoration of full tensile strength due to resin injection repair is not expected.

Flexural testing of repaired composite specimens is performed using three- or four-point bending. Three-point bending results in a complex stress state at the repair site and so four-point bending is preferred. ASTM standard D6272 [32] governs four-point bending of composite specimens and allows a load span to support span ratio of one third or one half. The region inside the load span is subject to a constant bending moment for small deflections. At large deflections peel stresses are amplified, testing the strength of any bonds forming part of the repair. Several authors have used four-point bending to assess the strength of repaired composite specimens [13,33–37].

In this paper, carbon fibre epoxy resin specimens were impacted using a drop tower instrument and repaired using a novel resin injection technique. The adhesive used in this study was selected due to its low viscosity at room temperature and relatively high glass transition temperature. While the paper presents an assessment of the repair technique in restoring the strength and stiffness of the laminate using a variety of residual strength tests, the primary aim of the paper is to investigate the validity of each residual strength test technique and to determine if a single test technique can be used to assess composite repair success. There currently exists no comparison study of the effect of specimen size on the compressive strength of repaired specimens. Equally while the compressive strength of repaired solid laminate specimens is commonly assessed, there exists no study comparing this compressive strength with the flexural strength of these repaired specimens. The study addresses both these areas by investigating the residual strength of pristine, damaged and repaired specimens through CAI, large scale compression after impact (LCAI), tensile and four-point bend testing.

2. Experimental

2.1. Materials

Unidirectional carbon fibre pre-impregnated material known as HTA6376 (Hexcel Composites Ltd., Cambridge, UK) is an aerospace grade carbon fibre epoxy resin composite material. This material was chosen as it has highly aligned fibres in each ply, making it more susceptible to significant stiffness and strength reductions when fibre breakage occurs. In addition, it has a less tough matrix than more modern aerospace grade materials, so is more susceptible to matrix cracking and ply delamination. A quasi-isotropic layup of $[45]_{4s}$ was used for all specimens, resulting in a thickness of approximately 4 mm. All laminates were cured in an autoclave (TC 1000 THPT, LBBC, UK) under a pressure of 7 bar and at a temperature of 178 °C for 3 h. CAI specimens were cut to 150 mm × 100 mm. LCAI specimens were cut to 280 mm × 163.5 mm. Tensile specimens were cut to 550 mm × 84 mm. Four point bend specimens were cut to 550 mm × 100 mm.

The adhesive used in this study was CA406, a commercially available cyanoacrylate from Henkel Ireland and was used without modification [38]. CA406 was selected due to its very low viscosity of 12–22 mPas, relatively high glass transition temperature, low volatility and fast curing time. All specimens repaired with this adhesive were subjected to a cure cycle of 24 h at room temperature followed by 24 h at 90 °C.

2.2. Introduction of impact damage

A drop tower instrument was used to introduce impact damage to specimens according to ASTM standard D7136 [39]. This method of damage introduction simulates typical in-service damage on composite aircraft structures [40]. However, drop tower damage in composites has been found to be inconsistent with the delaminated area varying significantly [40]. This is due to the rapid introduction of delaminations and matrix cracks that may result in isolated areas of damage. In this study, ultrasonic c-scans were carried out to determine the extent of damage after each impact test.

CAI and LCAI specimens were clamped to the drop tower fixture using four toggle clamps. Tensile and four-point bend specimens were clamped to the drop tower fixture using two large g-clamps. All clamps had rubber attachments to avoid damaging the specimens during clamping. CAI, tensile and four-point bend specimens were impacted using the standard cut-out of 125 mm x 75 mm in the base of the drop tower instrument. LCAI specimens were impacted using a cut-out of 255 mm × 138.5 mm.

An impact energy of 20 J was selected for all specimens. The indenter consisted of a hemispherical head of diameter 16 mm.

2.3. Repair procedure

A resin injection repair procedure was performed on damaged specimens similar to that performed by other authors [9,41,42,10], see Fig. 1. This repair method involves drilling several inlet holes in the damaged specimen and placing the specimen on a steel baseplate. An injection port is placed over the inlet holes and a vacuum bag placed over the specimen. A pump is used to create a vacuum within the vacuum bag allowing the adhesive to be injected through a needle inserted into the injection port. When the needle containing adhesive punctures the vacuum bag, the adhesive is pulled into the inlet holes drilled in the specimen. As the adhesive has a very low viscosity, it is also pulled into matrix cracks and delaminations connected to the inlet holes.

2.4. CAI procedure

CAI testing was performed according to ASTM standard D7137 [14] to assess the ultimate compressive strength of specimens, σ_{ucs}^{CAI}. The length, width and thickness of each specimen was measured prior to testing. The specimen was placed in the CAI rig with all bolts tightened to 7 Nm using a torque wrench, see Fig. 2(a).