Composites: Part A 41 (2010) 902–912

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Bonded repairs for carbon/BMI composite at high operating temperatures

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ARTICLE INFO

Article history:
Received 25 October 2009
Received in revised form 9 March 2010
Accepted 10 March 2010

Keywords:
A. Prepreg
B. Adhesion
C. Stress concentrations
D. Mechanical testing

ABSTRACT

The increased use of carbon reinforced polymer composite structures in civilian and military aircraft has produced new challenges for on-aircraft bonded repairs. Carbon/bismaleimide (BMI) composite structure provides an added complexity associated with the application of adhesively bonded repairs. Commercially available carbon/BMI composite usually requires a post-cure temperature in excess of 220 °C to achieve the high strength properties at elevated operating temperatures. Application of bonded repairs in situ often places an upper limit on the temperatures that can be employed for curing the adhesive at 177 °C. Consequently, the adhesive bond needs to achieve similar mechanical properties to the parent matrix material without the benefit of the high post-cure temperature. The current work examines a range of repair options that can be used to recover strength and the selection of adhesives and processes to successfully apply the repairs using vacuum assisted pressure.

1. Introduction

Carbon/bismaleimide (BMI) composite may be employed in critical load-bearing aircraft structures that experience high operating temperatures. The upper temperature testing by the manufacturer of Cycom® 5250-4 prepreg system with IM7 carbon fibres was around 177 °C in the wet condition [1]. By contrast Cycom® IM7/977-3 has an upper use temperature around 132 °C [2]. The relative compression and short beam shear strengths for these two systems indicates the carbon/BMI system can offer 15–30% wet strength improvement over IM7/977-3 at 132 °C or equivalent wet strength at 20 °C to 60 °C higher temperatures [1,2].

Despite the advantages offered by carbon/BMI for higher temperature structural applications, difficulties arise in undertaking in situ repairs where the high temperature properties need to be restored. The upper cure temperature for on-aircraft repairs may be limited to 177 °C to remain below the auto-ignition temperature for the aviation fuel and prevent high temperature transmission into aluminium substructure. High internal vapour pressures generated during high temperature cure may also lead to separation of the composite skin from honeycomb skins. Whilst the carbon/BMI achieves the high temperature properties with a post-cure temperature in excess of 220 °C, the repair adhesive needs to re-establish the BMI properties with the 177 °C cure temperature limit. A further complication for in situ repairs is pressure application during adhesive cure. Pressure may be applied using vacuum bag arrangements, to reduce the foot-print of the repair equipment. As most adhesives are designed for use in high pressure autoclaves, vacuum assisted pressure may cause high bondline porosity [3].

Previous work on bismaleimide adhesive using vacuum pressurisation found that voiding could be reduced if the vacuum was released at the adhesive flow temperature and a small positive pressure was maintained during cure [4]. If small positive pressure can be applied during aircraft repair this technique could be considered, however, additional equipment requirements would need to be assessed.

The bonded repair should restore the original stiffness, static strength, durability and damage tolerance [5]. Creep of moisture laden adhesive under high temperature loading also needs consideration [6,7]. Common bonded repair designs [8,9] performed on the aircraft structure may be limited to options such as an external doubler, step-lap or scarf repair (Fig. 1). The bonded doubler strength may be compromised by geometrically non-linear bending, which increases the stress concentration adjacent to the damage cut-out region [10]. By contrast, the scarf or step-lap configuration should minimise secondary bending effects, but will be more difficult to apply.

Design of the bonded repair must consider the full temperature and humidity environment that the component will experience. At high operating temperatures the effect of moisture on the adhesive and composite may be significant. The strength of the adhesive and composite matrix is closely related to their glass transition temperatures, T_g, which are highly dependent on the cure temperature and moisture state. Unlike a metallic patch over metallic structures, bonded composite repairs are permeable to moisture throughout the length of the joint and consequently the bondline will absorb

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doi:10.1016/j.compositesa.2010.03.006

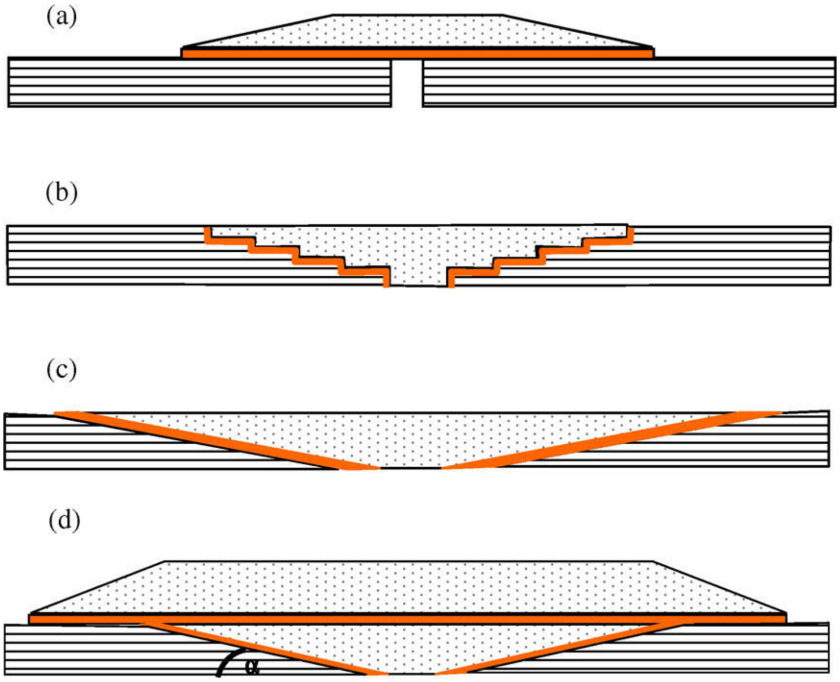

Fig. 1. Repair configurations that may be employed in cases where only single-sided access is available (a) doubler, (b) step-lap, (c) scarf and (d) scarf-doubler bonded repairs.

moisture at a significantly faster rate than equivalent metallic structures. Consequently, the limiting strength for composite repairs bonded to high temperature composite materials, such as carbon/BMI, may often be in the hot/wet condition [10].

Previously, work has examined the use of bismaleimide adhesive in conjunction with a second low temperature adhesive to provide optimal joint properties over a large temperature range [4,11,12]. The use of a low temperature adhesive with the high temperature BMI adhesive worked for dissimilar adherends where the overall joint strength was limited by the low temperature strength of the brittle BMI adhesive. Whilst this work provided a novel solution to the low temperature strength of some BMI adhesives it is inapplicable to the current study where similar composite adherends are used. Additionally, BMI adhesives cannot easily be used for repair, due to their high post-cure temperature, which precludes on-aircraft use.

The following work examines the design and application of bonded repairs to carbon/BMI composite structure. Repair options considered single-sided access, cure temperature limited to 177 °C and vacuum pressurisation for usage temperatures between −55 °C (cold/dry) and 177 °C in the wet condition (hot/wet). Potential adhesives were screened using dynamic mechanical thermal analysis (DMTA) and differential scanning calorimetry (DSC) [13] and surface treatment options were examined. Validation of repair design was performed using representative joints. The overall aims of the work were to develop practical repair techniques for high temperature, highly loaded carbon/BMI composite structure where the repairs were required to be applied in situ and the repair adhesive cure was limited to 177 °C.

2. Experimental

2.1. Characterisation and testing

Cytec's oxyamide film adhesive FM32 (488 g/m^2) and epoxy film adhesive FM355 (366 g/m^2) were cured 177 °C /4 h and 177 °C/1 h, respectively. AF131-2 (366 g/m^2) epoxy film adhesive from 3 M was cured 90 min at 177 °C. Cytec IM7-G/5250-4 carbon/BMI unidirectional prepreg tape (145 g/m^2) was cured at 586 kPa and 177 °C for 6 h with a 226 °C/ 6 h post-cure. The adhesive glass transition temperature (T_g) used single cantilever bending of 0.1% strain at 1.0 Hz and a ramp rate of 5 °C/min. The T_g was measured from the onset of the storage modulus change for the adhesive, in the dry and moisturised state. Differential scanning calorimetry (DSC) measured the extent of cure from the residual exotherm of the cured adhesive samples.

Mini-scarf joints used 12 ply unidirectional composite adherends with a 3° scarf angle (Fig. 2) and the surface treatment procedures detailed in Table 1 were characterised using contact angle and surface analysis measurements [13]. The 3° scarf angle was machined using a computer controlled router with a diamond encrusted tool-bit. Bonding at 275 kPa or −100 kPa used methods provided in Table 1 with an envelope bag to restrain adhesive flow. Conditioned joints had 1.2% moisture uptake. Thick adherend lap shear testing used Al2024–T351 aluminium in accordance with the methods detailed in ASTM D5656 [14] and a grit-blast and epoxy silane treatment [15]. Moisture conditioning took 75 to 100 days at 70 °C/95% R.H. Mode II testing used the three-point bend end-notch flexure test [16] with 15-ply unidirectional laminates bonded using FM32.

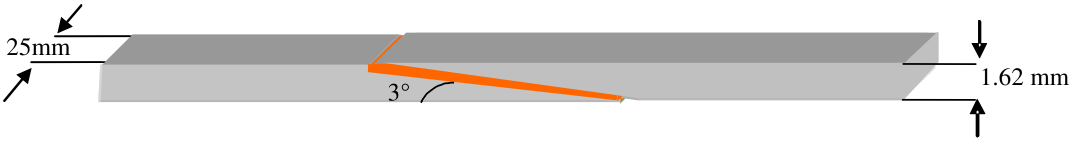

Fig. 2. Mini-scarf configuration used to examine adhesive shear strength of composite bonded joints.