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The enhancement of adhesively-bonded aerospace-grade composite joints using steel fibres

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ABSTRACT

Ductile steel fibres with high stiffness of 193 GPa, high strain-to-failure of 20% and diameter of 22 μm were used to enhance fracture toughness of composite adhesive joints. Two nano-toughened structural adhesives with significantly different mechanical and fracture properties were used to bond aerospace-grade composite substrates. Steel fibres were placed in the adhesive layer either longitudinally or transversely to the crack growth direction. Mode-I and mode-II fracture behaviour of the composite adhesive joints were studied using double cantilever beam test and end-loaded split test, respectively. The incorporation of steel fibres significantly increased both mode-I and mode-II fracture toughness, irrespective of the adhesive used. The improvement of mode-I and mode-II fracture energies was more pronounced when the steel fibres were placed transversely to the crack growth direction, due to the increased level of steel fibre bridging.

1. Introduction

The automotive and aerospace industries have made considerable efforts in producing lightweight constructions by incorporating carbon fibre reinforced plastic composites (CFRPs), which possess high stiffness, good tensile properties and relatively low densities [1]. One of the main technique for joining CFRPs is to use structural adhesive [2,3].

Epoxies are extensively used as the matrices of structural adhesives [4] due to their superior engineering properties, such as high stiffness, high strength, low creep and excellent thermal stability [5,6]. However, pure epoxies have inherently low fracture toughness and hence poor crack resistance. This is commonly overcome by blending second phase modifiers, such as silica particles [7–9], rubber particles [10–12] and carbon nanotubes [13,14] into epoxies. Among different types of modifiers, rubber particles have shown superior performance in enhancing the fracture toughness of epoxy adhesives. For example, it has been reported that the addition of core–shell rubber nanoparticles increased the fracture energy of a structural epoxy adhesive by over 10 times to approximately 5.5 kJ/m^2 [12]. Consequently, rubber-modified epoxy adhesives are widely used for structural applications in aerospace and automotive industries [4,15]. However, it is generally accepted that an optimum rubber content exists, above which, the fracture toughness of adhesive joints decreases with increasing rubber content [10,16]. Hence, further enhancement of rubber-toughened adhesive joints is still desirable, especially when used in load bearing applications.

Previous attempts to improve the fracture toughness of adhesive joints using different types of fibres have shown substantial success. Sun et al. [17] employed randomly-distributed short aramid fibres with a length of 6 mm in epoxy adhesive joints. It was found that the incorporation of aramid fibres increased the interfacial fracture energy of the adhesive joints from approximately 30 J/m^2 to 335 J/m^2. Nam et al. [18] and Bang et al. [19] studied the effect of adding chopped glass fibres in the adhesive layer on the fracture toughness of adhesive bonded joints with stainless steel and aluminium as adherend. It was reported that adding 20 vol.% glass fibres, with a length of 3 mm, increased the fracture energy of the Polyurethane adhesive joints from 442 J/m^2 to 3170 J/m^2. Landani et al. [20] reported that adding 1 wt% carbon nano-fibres in the adhesive layer significantly increased the fracture energy of composite adhesive joints from 134 J/m^2 to 1642 J/m^2. The toughening performance of fibre reinforced adhesive joints is intrinsically dependent on the mechanical properties (stiffness and strain to failure) and dimension (length and diameter) of the fibres, on top of the other factors, such as fibre-matrix adhesion, fibre volume fraction and orientation etc. Recently, a new class of stainless steel fibres with diameter of 2–40 μm were developed by Bekaert (Belgium). They possess far more desirable properties, i.e. stiffness of 193 GPa and strain-to-failure of 20%, for structural applications when compared to other fibres. For example, the strain-to-failure of carbon and glass fibres is only in the range of 1.5–4%, while other fibres, such as polymeric

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[21] and natural fibres [22], have higher strain-to-failure (15–30%), but much lower stiffness (< 30 GPa) [23]. Gallens et al. [23–25] and Allare et al. [26] studied the mechanical properties of steel fibre reinforced plastics and reported a maximum of 5 times higher strain-to-failure than typical carbon or glass fibre composites. The high weight of the steel fibre reinforced plastics restricts their wide application. However, the high stiffness and high strain-to-failure of the steel fibres make them attractive candidates as reinforcement of adhesive joints.

The goal of this research is to explore the potential of using ductile steel fibres to enhance the composite adhesive joints for structural applications. Two structural adhesives with significantly different mechanical and fracture properties were used to join aerospace-grade CFRPs. Steel fibres with a diameter of 22 μm were incorporated in the CFRP adhesive joints. Double cantilever beam (DCB) and end-loaded split (ELS) tests were performed to measure the Mode-I and mode-II fracture behaviour of the adhesive joints.

2. Experimental

2.1. Materials

Two structural epoxy adhesives were supplied in the form of one-component paste by Henkel (Ireland). These adhesives contain the same epoxy matrix, but different volume fractions of core-shell rubber (CSR) nanoparticles, i.e. 8 vol.% and 38 vol.%. The adhesives are referred to as CSR8 and CSR38 respectively in the rest of this paper. The diameters of the CSR nanoparticles and the rubber cores were measured to be 203.4 nm and 169.6 nm respectively [10]. The curing schedule for the adhesives is 90 min at 180 °C. The stress-strain curves of the adhesives measured using uniaxial tensile tests are shown in Fig. 1(a) [10], while the fracture energy of the adhesives determined from tapered double cantilever beam tests with 1 mm bond gap thickness is shown in Fig. 1(b) [12]. It is clear that these two adhesives possess significantly different mechanical properties and fracture toughness, i.e. CSR38 adhesive has much higher ductility and fracture toughness but lower Young's modulus and tensile strength than CSR8 adhesive.

The stainless steel fibres were supplied by Bekaert (Belgium) in a form of continuous bundle, see Fig. 2. The bundle has 4000 steel fibres. The following properties of the steel fibres were provided by the manufacturer, a stiffness of 193 GPa, a strain-to-failure of 20% and a diameter of 22 μm.

The carbon fibre composite employed in this work is aerospace-grade prepreg (Hexply 8552/5H supplied by Bombardier Aerospace, Belfast) that consists of 5-harness carbon fibre (AS4) weave pre-impregnated with an epoxy resin. The composite laminates were cured in–house using a vacuum bagging layup procedure according to the instructions from the supplier. A seven ply prepreg layup was first prepared with a layer of wet peel-ply (Hysol EA9895 supplied by Henkel) on top, and then cured inside a pressclave with an internal pressure of 80 psi (approximately 5.5 bar) applied in the chamber from a compressed air supply line. The cure cycle consists of a 2 h ramp from room temperature to 180 °C followed by a 2 h hold, or dwell, at 180 °C. Once cured, the composite panels were machined to required dimension using a diamond grinding disc.

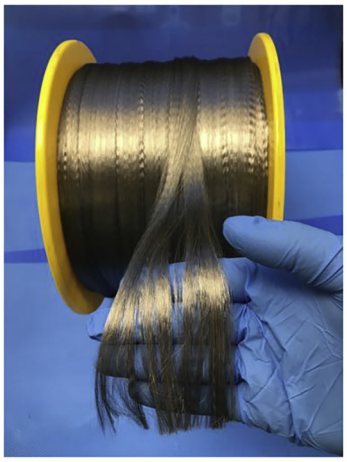

Fig. 2. The stainless steel fibre bundle containing 4000 filaments. The diameter of the fibres is 22 μm.

2.2. Adhesive joint preparation and testing

Mode-I DCB and mode-II ELS tests were carried out in order to measure the fracture energy of the composite adhesive joints according to the standards BS-7991-2001 [27] and ISO: 15114:2014 [28], respectively. Schematics of the DCB and ELS tests are given in Fig. 3. The specimens have a nominal width of 25 mm and length of 150 mm for DCB tests or 180 mm for ELS tests with an initial crack starter length of 45 mm for DCB test or 65 mm for ELS test from the load-line.

The bonding surfaces of the composite substrates were prepared using wet peel-ply to ensure good adhesive bonding strength. A PTFE film with a thickness of 12.5 μm was placed in the adhesive layer at the loading end to introduce the crack starter (this is shown as green lines in Fig. 3). Two spacers were placed at each end of the joint to obtain an adhesive bond thickness of 0.2 mm. The steel fibres were placed in the adhesive layer manually either with a longitudinal or a transverse orientation to the crack growth direction, with a density of 40 filaments per millimetre. The assembled joints were placed into a pre-heated oven at 180 °C for 90 min to cure. After the curing, the joints were left in the oven to cool down slowly to room temperature to minimise residual stresses generated in the adhesive joints.

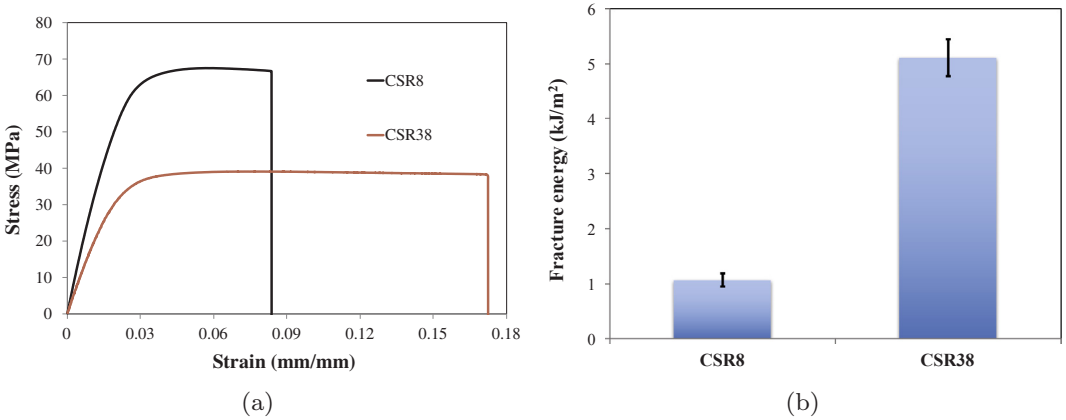

Fig. 1. Comparison of the adhesive properties: (a) stress-strain curves [10], (b) mode-I fracture energy [12].